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EXPLOSION EFFECTS AND PROPERTIES: PART II – EXPLOSION EFFECTS IN WATER

EDITED BY: MICHAEL M. SWISDAK, JR.

RESEARCH AND TECHNOLOGY DEPARTMENT

22 FEBRUARY 1978

NAVAL SURFACE WEAPONS CENTER

Dahlgren, Virginia 22448 • Silver Spring, Maryland 20910

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This report updates and, therefore, supersedes Section B (Explosions in Water) of an earlier report, NOLTR 65-218. The tables, charts, and graphs contained herein show the effects of explosives detonated underwater. This compilation enables the user to find, in one report, much of the information he requires without having to do an extensive literature search. A future

report will be issued to update Section D (Explosives Effects and Properties), of NOLTR 65-218

The data presented in this report are presented in SI (system internationale) units; tables for conversion to English units are provided.

SUMMARY

This report supersedes Section B (Explosions in Water) of NOLTR 65-218. It includes data acquired after the publication of NOLTR 65-218 as well as data previously appearing in that report that is still applicable. All data are presented in a new format to facilitate dissemination to the user. Section A of TR 65-218 has already been superseded by NSWC/WOL/TR 75-116; Section D of TR 65-218 will be superseded by a forthcoming report. In a report of this nature, errors are bound to creep in; the Center would appreciate having such errors brought to its attention, so that subsequent editions of this report may be more accurate. Please address correspondence to: Commander, Naval Surface Weapons Center, White Oak, Silver Spring, MD 20910; Attention: Code WR-15.

Mention of commercial products in this report implies neither endorsement nor criticism by the Center.

Substantial contributions to this report were received from D. E. Phillips, T. B. Heathcote, J. B. Dempsey, J. B. Gaspin, G. A. Young, and E. A. Christian.

This compilation was accomplished under Naval Sea Systems Command Task Number SF33-354-316/18460.

J. W. Enig

J. W. ENIG
By direction

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SI UNITS

QUANTITY	SI UNIT NAME
FORCE	NEWTON (N)
MASS	KILOGRAM (kg)
TIME	SECOND (s)
LENGTH	METER (m)
FREQUENCY	HERTZ (Hz)
VOLUME	CUBIC METER (m^3)
SPEED	METER/SECOND (m/s)
DENSITY	KILOGRAM/CUBIC METER (kg/m^3)
ENERGY	JOULE (J)
WORK	NEWTON-METER (N-m)
PRESSURE	PASCAL (Pa)
IMPULSE	PASCAL-SECOND (Pa-s)
ENERGY FLUX DENSITY	METER-PASCAL (m-Pa)
TEMPERATURE	DEGREE KELVIN (°K)

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CONVERSION FACTORS

TO CONVERT	INTO	MULTIPLE BY
METERS	FEET	3.281
KILOGRAMS	POUNDS	2.2046
MEGAPASCALS (MPa)	psi	145.038
$m/kg^{1/3}$	$ft/1b^{1/3}$	2.5208
$kg^{1/3}/m$	$1b^{1/3}/ft$	0.3967
$kg^{1/3}$	$1b^{1/3}$	1.3015
$m/kg^{1/4}$	$ft/1b^{1/4}$	2.6929
kPa-s	psi-sec	0.14504
$kPa\text{-}s/kg^{1/3}$	$psi\text{-}sec/1b^{1/3}$	0.11144
m-kPa	in-psi	5.7073
$m\text{-}kPa/kg^{1/3}$	$in\text{-}psi/1b^{1/3}$	4.3852
$m^{4/3}/kg^{1/3}$	$ft^{4/3}/1b^{1/3}$	3.7453
$m^{5/6}/kg^{1/3}$	$ft^{5/6}/kg^{1/3}$	2.0678
kg/m^3	$1b/ft^3$	0.06243
FEET	METERS	0.3048
POUNDS	KILOGRAMS	0.4536
psi	MPa	0.0068946
$1b^{1/3}$	$kg^{1/3}$	0.7683
$ft/1b^{1/3}$	$m/kg^{1/3}$	0.3967
$1b^{1/3}/ft$	$kg^{1/3}/m$	2.5208
$ft/1b^{1/4}$	$m/kg^{1/4}$	0.3714
psi-sec	kPa-s	6.8947
$psi\text{-}sec/1b^{1/3}$	$kPa\text{-}s/kg^{1/3}$	8.9738
in-psi	m-kPa	0.17521
$in\text{-}psi/1b^{1/3}$	$m\text{-}kPa/kg^{1/3}$	0.22804
$ft^{4/3}/1b^{1/3}$	$m^{4/3}/kg^{1/3}$	0.2670
$ft^{5/6}/1b^{1/3}$	$m^{5/6}/kg^{1/3}$	0.4836
$1b/ft^3$	kg/m^3	16.017

CHAPTER 1. INTRODUCTION AND DEFINITIONS

This report supersedes Section B (Explosion Effects in Water) of NOLTR 65-218, "Explosives-Effects and Properties," published in 1967. The tables, charts, and graphs contained herein show the effects of explosives detonated underwater. This compilation enables the user to find, in one report, much of the information he requires without having to do an extensive literature search. Each chapter includes problem examples which demonstrate the use of the data presented.

The detonation of a high explosive charge underwater converts the solid explosive material into gaseous reaction products which have an exceedingly high pressure. This pressure is transmitted to the surrounding water and propagates as a shock wave in all directions.

Figure 1-1 illustrates the pressure-time history which is observed in the water at a fixed distance from the point of explosion. Upon arrival of the shock wave, the pressure rises practically instantaneously to the peak value. Subsequently, the pressure decreases at a nearly exponential rate. It takes only a short time until the pressure has decreased to 1/e or 36.8% of its maximum value (the time required for the pressure to fall to a value of 1/e is defined as the decay constant). The shock wave peak pressure and the decay constant depend on the charge material, charge weight, and the distance to the point of observation.

Figure 1-1 also shows that subsequent to the shock wave, other pressure pulses occur. These pulses arise from a much slower phenomenon, namely the pulsating of the gas bubble which contains the gaseous products of the explosion. The high pressure of the gas causes an initially rapid expansion of the bubble and the inertia of the outward moving water carries it far beyond the point of pressure equilibrium. The outward motion stops only after the gas pressure has fallen substantially below the ambient pressure. Now the higher surrounding pressure reverses the motion. Again, the flow overshoots the equilibrium and when the bubble reaches its minimum size, the gas is recompressed to a pressure of several hundred atmospheres. At this point we have effectively a second "explosion" (i.e., the generation of an acoustic pulse without a shock wave) and the whole process is repeated. The bubble oscillates in this way several times.

In Figure 1-1, the position and the size of the bubble are shown for a few specific moments which correspond to the pressure-time curve as indicated above. The pressure-time history reflects the low gas

pressure during the phases where the bubble is large and it shows the pressure pulses which are emitted from the bubble near its minimum.

The period of the bubble pulsations is very long when compared with the high pressure (shock wave) portion of the pressure-time history of an explosion. In particular, this duration is long enough for gravity to become effective. Such a bubble has great buoyancy and, therefore, migrates upward. However, it does not float up like a balloon, but shoots up in jumps.

In Figure1-1, the dotted curve represents the position of the bubble center as a function of time. This curve shows that the rate of rise is largest when the bubble is near its minimum, but is almost zero when the bubble is large. (Note that Figure 1a is a time plot of bubble position and size. It must not be interpreted moving vertically upward.) (Reference 1-1)

Figure1-2 is an expansion of a portion of the pressure-time plot shown in Figure 1a. On it are shown and defined some of the parameters of particular interest in underwater explosions, namely: (1) shock wave peak pressure, (2) shock wave time constant, (3) shock wave impulse, and (4) shock wave energy flux density (Energy flux density is often referred to as simply "energy". In this report, the terms are synonymous).

When comparing the performance of underwater explosives for a specific use, five ratios are generally used. These are:

(1) <u>Equal Weight Ratio (D_{wd})</u>: The ratio of the outputs with respect to a particular parameter (peak pressure, time constant, impulse, or energy flux density) for equal weights of two explosives at the same distance. (This is of interest in the design of weight-limited weapons.) (Reference 1-2)

(2) <u>Equal Volume Ratio (D_{vd})</u>: The ratio of outputs with respect to a particular parameter for equal volumes of two explosives as measured at the same distance. (This is of interest in the design of volume-limited weapons.) (Reference 1-2)

(3) <u>Equivalent Weight Ratio (W_{Dd})</u>: The ratio of weights of two explosives required to produce the same magnitude of a particular parameter at the same distance. (Reference 1-2)

1-1 Snay, H. G., "Hydrodynamics of Underwater Explosions," reprinted from NAVAL HYDRODYNAMICS, Publication 515, National Academy of Sciences -- National Research Council, 1957

1-2 "Analysis and Correlation of Underwater Explosion Data at NOL," Phillips, D. E., NOLTR 69-192, January 1970.

(4) Relative Bubble Energy (RBE)*: The cube of the ratio of the first bubble period constants (K's):

$$RBE = \left(\frac{K_{experimental}}{K_{reference}}\right)^3$$

(5) Relative Potential Bubble Energy (RPBE)*: The cube of the ratio of the maximum bubble radius constants (J's):

$$RPBE = \left(\frac{J_{experimental}}{J_{reference}}\right)^3$$

Figure 1-3 presents a "universal nomograph," i.e., one that is independent of a particular system of units, for determining the similitude parameters used in the following chapters.

Table 1 presents a list of many of the explosives used in underwater explosion work and presents their composition and density.

*Bubble period constant and bubble radius constant are defined in Chapter 10.

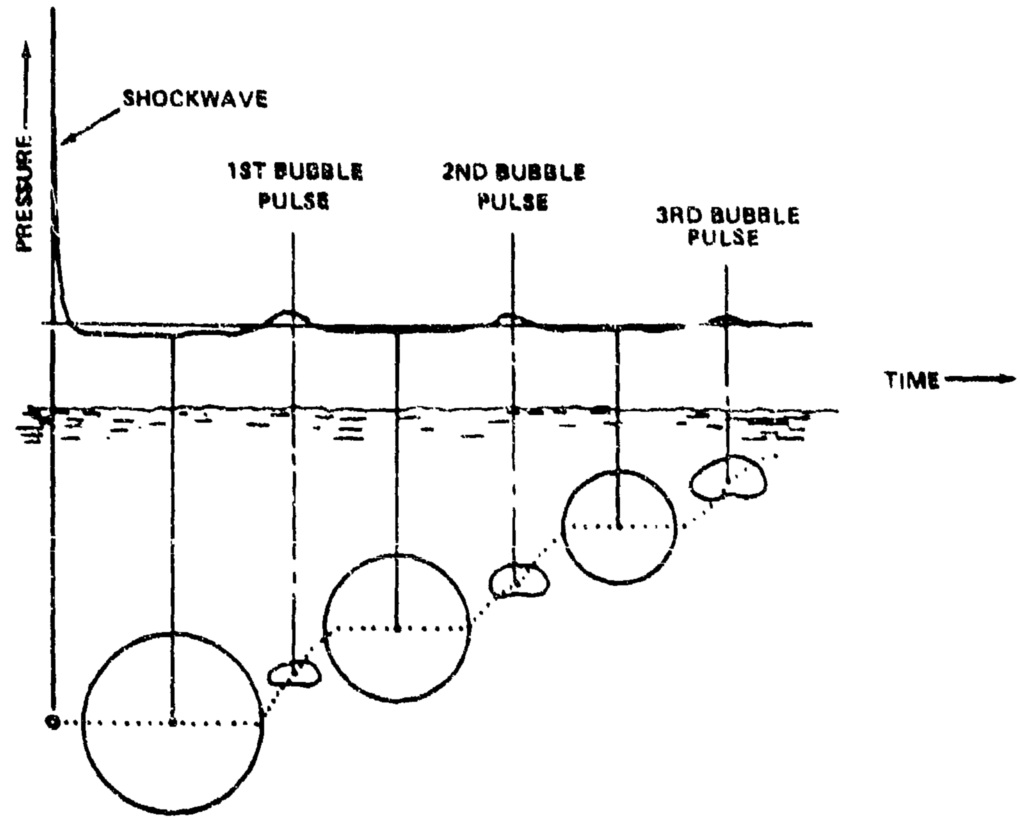
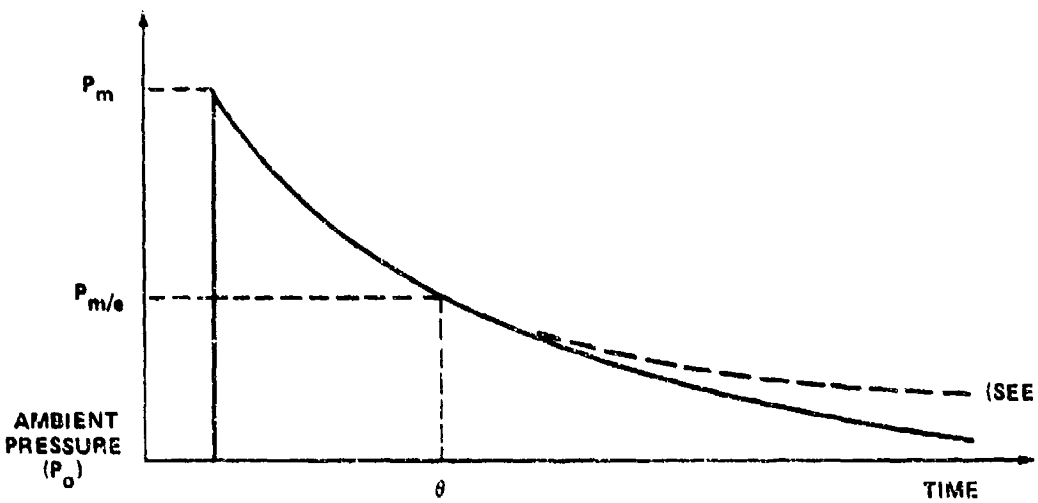


FIG. 1-1 PRESSURE WAVES AND BUBBLE PHENOMENA OF UNDERWATER EXPLOSIONS. THE UPPER PART SHOWS A PRESSURE-TIME PLOT, THE LOWER, THE POSITION AND SIZE OF THE BUBBLE FOR SPECIFIC MOMENTS WHICH CORRESPOND TO THE CURVE ABOVE AS INDICATED BY THE VERTICAL LINES.



(1) PEAK OVERPRESSURE (P) — PEAK OVERPRESSURE ABOVE AMBIENT PRESSURE (ASSUMED TO BE OF THE FORM $P(t) = P_m e^{-t/\theta}$)

(2) TIME CONSTANT (θ) — THE TIME REQUIRED FOR THE PRESSURE TO FALL TO A VALUE OF P_m/e

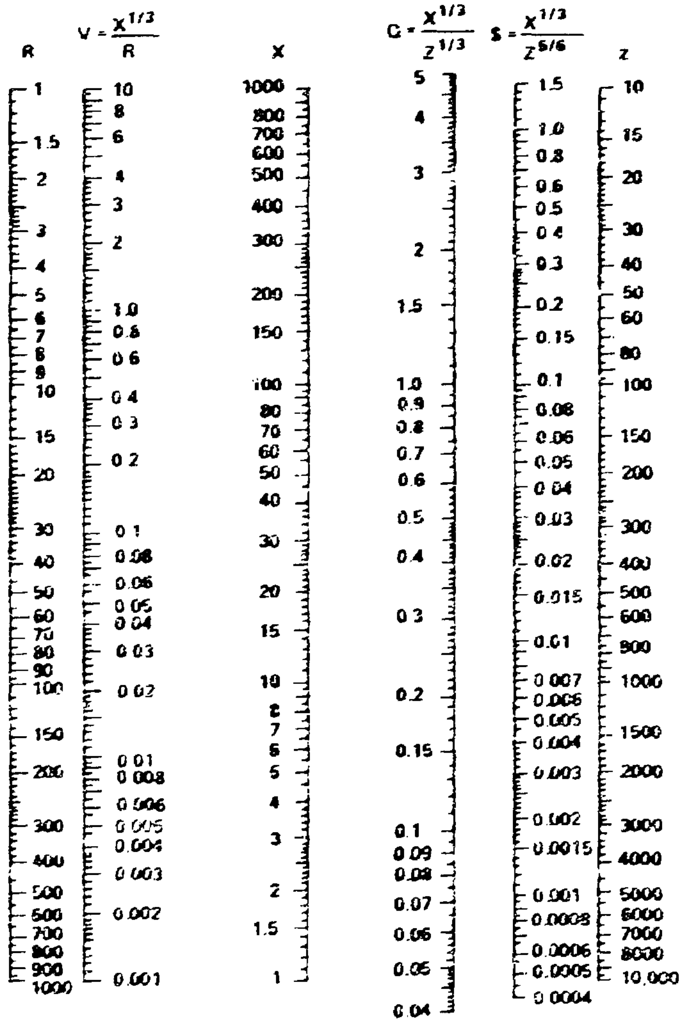
(3) IMPULSE (I) — $\int_0^t P(t)dt$ (THE INTEGRATION TIME t IS USUALLY TAKEN TO BE 5θ)

(4) ENERGY FLUX DENSITY (E) — $\frac{1}{\rho_o C_o} [1-2.422 \times 10^{-4} P_m - 1.031 \times 10^{-8} P_m^2] \int_0^t P^2(t)dt$

WHERE THE TWO NEGATIVE TERMS REPRESENT THE CORRECTION FOR AFTERFLOW. $\rho_o C_o$ IS THE ACOUSTIC IMPEDANCE OF THE MEDIUM. (THE INTEGRATION TIME t IS USUALLY TAKEN TO BE 5θ).

NOTE 1: IT IS GENERALLY ASSUMED, AND EMPIRICALLY ESTABLISHED, THAT OVER RANGES OF INTEREST, THE SHOCK WAVE PRESSURE DECAYS EXPONENTIALLY TO ABOUT ONE TIME CONSTANT; AFTER THAT THE PRESSURE DECAYS MORE SLOWLY.

FIG. 1-2 DEFINITIONS OF SHOCK WAVE PARAMETERS



THE SIMILITUDE EQUATIONS FOR UNDERWATER EXPLOSION PARAMETERS EMPLOY FUNCTIONS OF THE CHARGE WEIGHT, RANGE AND DEPTH.
FOR CONVENIENCE THESE FUNCTIONS ARE PRESENTED HERE IN NOMOGRAM FORM.

THESE NOMOGRAMS WERE CACULATED USING THE FOLLOWING EQUATIONS:

$V = X^{1/3}/R$ } UNDERWATER SHOCK WAVE SIMILITUDE PARAMETER

$Q = X^{1/3}/Z^{1/3}$
$S = X^{1/3}/Z^{5/6}$ } UNDERWATER BUBBLE SIMILITUDE PARAMETERS *

SYMBOLS. X = CHARGE WEIGHT OR RADIOCHEMICAL YIELD
R = SLANT RANGE
Z = HYDROSTATIC HEAD = $D + D_O$

WHERE D = CHARGE DEPTH
D_O = ATMOSPHERIC HEAD (IN EQUIVALENT WATER DEPTH UNITS)

NO UNITS HAVE BEEN ASSIGNED SO THAT THE NOMOGRAMS ARE APPLICABLE TO BOTH CONVENTIONAL AND NUCLEAR EXPLOSIONS AND FOR ANY SYSTEM OF UNITS.
IN ORDER TO MAINTAIN AS HIGH ACCURACY AS POSSIBLE FOR READING THESE NOMOGRAMS, THE SCALES HAVE BEEN LIMITED. IT IS A SIMPLE MATTER TO CONVERT THE SCALES TO READ ANY DESIRED RANGE OF VALUES, AS INDICATED BY THE TABLE BELOW.
* SUBSEQUENT CHAPTERS WILL INDICATE PROPER SELECTION OF THE SCALING FORM OF Z.

FOR UNDERWATER SHOCK WAVE PARAMETER $V = X^{1/3}/R$	
IF R SCALE MULTIPLIED BY 1000	MULTIPLY V SCALE BY 10^3
" X " " " 1000	" V " " 10
FOR UNDERWATER BUBBLE PARAMETERS $Q = X^{1/3}/Z^{1/3}$ AND $S = X^{1/3}/Z^{5/6}$	
IF X SCALE MULTIPLIED BY 1000	MULTIPLY Q SCALE BY 10
" Z " " " 1000	" Q " " 10^1
" X " " " 1000	" S " " 10
" Z " " " 1000	" S " " 3.162×10^3

FIG. 1-3 NOMOGRAM FOR DETERMINING THE VALUES OF THE SIMILITUDE PARAMETERS

TABLE 1 NOMINAL EXPLOSIVE PROPERTIES

MATERIAL	COMPOSITION (PERCENT BY WEIGHT)	DENSITY (kg/m^3)
TNT		1600
RDX		1820
PETN		1760
PENTOLITE	50/50 PETN/TNT	1710
HBX-1	40/38/17/5 RDX/TNT/Al/D-2 WAX	1720
HBX-3	31/29/35/5 RDX/TNT/Al/D-2 WAX	1840
H-6	45/30/20/5 RDX/TNT/Al/D-2 WAX	1760

CHAPTER 2. SIMILITUDE EQUATIONS

According to the principle of similarity, if the linear dimensions of a charge and all other lengths are altered in the same ratio for two explosions, the shock waves formed will have the same pressures at corresponding distances scaled by this ratio, if the times at which pressure is measured are also scaled by this same ratio (Reference 2-1). This principle leads directly to simple predictions of the values of the shock wave parameters at the point of observation based only upon the distance from the charge to the point of observation and the dimensions of the charge. Experimental data have indicated that these predictions take the form:

$$\text{PARAMETER} = K \left(\frac{W^{1/3}}{R}\right)^{\alpha} \qquad (1)$$

This chapter will present values for K and α for various high explosives for the shock wave parameters of interest. These values are presented in Table 2. Note also, that the range of validity of each equation is also presented in this table.

PROBLEM EXAMPLE

Compare the shock wave parameters produced at a range of 10 meters from the detonation of 100 kilograms of H-6 and Pentolite.

SOLUTION:

(1) $R = 10$ meters, $W = 100$ kg, $W^{1/3} = 4.642\ \text{kg}^{1/3}$

(2) $W^{1/3}/R = 4.642/10 = .4642\ \text{kg}^{1/3}/\text{m}$

(3) From Table 2, obtain the similitude parameters for both H-6 and pentolite and solve for the various parameters using a value of 0.4642 for $W^{1/3}/R$.

(4) For H-6:

$P = 59.2\ (.4642)^{1.19} = 23.75$ MPa

$\theta/W^{1/3} = 0.088\ (.4642)^{-.28} = 0.109\ \text{ms/kg}^{1/3}$

$\theta = .109 \times 4.642 = .506$ ms

$I/W^{1/3} = 6.58\ (.4642)^{.91} = 3.273\ \text{kPa-s/kg}^{1/3}$

2-1 UNDERWATER EXPLOSIONS, Cole, R. H., Dover Publications, 1965.

(4) For H-6 (Cont.):

$I = 3.273 \times 4.642 = 15.19$ kPa-s

$E/W^{1/3} = 115.3\ (.4642)^{2.08} = 23.37$ m-kPa/kg$^{1/3}$

$E = 23.37 \times 4.642 = 108.46$ m-kPa

For Pentolite:

$P = 56.5\ (.4642)^{1.13} = 23.74$ MPA

$\theta/W^{1/3} = 0.084\ (.4642)^{-.23} = .100$ ms/kg$^{1/3}$

$\theta = 0.100 \times 4.642 = 0.464$ ms

$I/W^{1/3} = 5.73\ (.4642)^{.91} = 2.850$ kPa-s/kg$^{1/3}$

$I = 2.850 \times 4.642 = 13.23$ kPa-s

$E/W^{1/3} = 92.0\ (.4642)^{2.04} = 19.22$ m-kPa/kg$^{1/3}$

$E = 19.22 \times 4.642 = 89.23$ m-kPa

(5) In summary:

	H-6	Pentolite
P_m (MPa)	23.75	23.74
θ (ms)	0.505	0.465
I (kPa-s)	15.19	13.23
E (m-kPa)	108.46	89.23

TABLE 2 SIMILITUDE CONSTANTS AND COEFFICIENTS FOR VARIOUS HIGH EXPLOSIVES

EXPLOSIVE	P_m		$\theta/W^{1/3}$		$I/W^{1/3}$		$E/W^{1/3}$		RANGE OF VALIDITY*	REF.
	K	α	K	α	K	α	K	α		
TNT	52.4	1.13	0.084	−0.23	5.75	0.89	84.4	2.04	3.4 - 138	2-2
PENTOLITE	56.5	1.14	0.084	−0.23	5.73	0.91	92.0	2.04	3.4 - 138	2-3
H-6	59.2	1.19	0.088	−0.28	6.58	0.91	115.3	2.08	10.3 - 138	2-4
HBX-1	56.7	1.15	0.083	−0.29	6.42	0.85	106.2	2.00	3.4 - 60	2-3
HBX-1**	56.1	1.37	0.088	−0.36	6.15	0.96	107.2	2.26	60 - 500	2-6, 2-7
HBX-3	50.3	1.14	0.091	−0.218	5.33	0.90	90.9	2.02	3.4 - 60	2-5
HBX-3**	54.3	1.18	0.091***	−0.218***	5.70	0.80	114.4	1.97	60 - 350	2-6

NOTE: ALL EQUATIONS ARE OF THE FORM $\text{PARAMETER} = K\left(\frac{W^{1/3}}{R}\right)^{\alpha}$

P_m = PEAK PRESSURE (MPa)

$\theta/W^{1/3}$ = REDUCED TIME CONSTANT (ms/kg$^{1/3}$)

$I/W^{1/3}$ = REDUCED IMPULSE (kPa-s/kg$^{1/3}$)

$E/W^{1/3}$ = REDUCED ENERGY FLUX DENSITY (m-kPa/kg$^{1/3}$)

W = CHARGE WEIGHT IN KILOGRAMS (kg)

R = SLANT RANGE IN METERS (m)

I AND E ARE INTEGRATED TO A TIME OF 5θ

*VALIDITY RANGE IS RANGE OF THE PRESSURE (IN MPa) OVER WHICH THE EQUATIONS APPLY

**EQUATIONS ARE BASED ON LIMITED DATA BEYOND ABOUT 130 MPa, AND SHOULD BE USED WITH CAUTION.

***SHOCK WAVE IS NOT EXPONENTIAL, BUT HAS A HUMP; THE SIMILITUDE EQUATION FITS THE PORTION OF THE WAVE BEYOND THE HUMP.

REFERENCES:

2-1 UNDERWATER EXPLOSIONS, Cole, R. H., Dover Publications, 1965.

2-2 Farley, T. E., and Snay, H. G., unpublished data.

2-3 "Revised Similitude Equations for the Underwater Shock wave Performance of Pentolite and HBX-1," Thiel, M. A., NAVWEPS Report 7380, February 1961.

2-4 Unclassified data from a classified reference.

2-5 Unclassified data from a classified reference.

2-6 "Improvements in Underwater Explosion Systems, Field Tests, Phase I," Coleburn, N. L., et al., NOLTR 63-198, December 1964.

2-7 "Improvements in Underwater Explosion Systems, Field Tests, Phase II," Coleburn, N. L., et al., NOLTR 66-22, June 1966.

CHAPTER 3. UNDERWATER SHOCK WAVE PARAMETERS FOR TNT

This chapter presents the values of the underwater shock wave parameters for a spherical TNT charge. These are in both a nomograph and tables; the values in the tables are the results of calculations based on certain discrete values of the charge weight.

It is assumed that the bottom and the surface do not affect the results.

The information presented here is based on the similitude parameters for TNT presented in Chapter 2.

PROBLEM EXAMPLE I:

At a distance where the pressure is 100 MPa from a 216 kg TNT charge, what are the other shock wave parameters?

SOLUTION:

(1) Enter Table 3-12 for W = 216 kg -- in the pressure column, when P = 100 MPa, read the other parameters:

R = 3.40 meters

θ = .442 ms

I = 57.14 kPa-s

E = 1609.69 m-kPa

PROBLEM EXAMPLE II:

What are the shock wave parameters 10 meters from a 1000 kilogram charge of TNT?

SOLUTION:

(1) Using the nomograph of Figure 3, connect 1000 on the W scale with 10 on the R scale and read:

P = 52 MPa

E = 810 m-kPa

I = 57 kPa-s

Then connect 1000 on the W scale with 10 on the inverted R scale and read:

θ = 0.82 msec

(2) Substitute directly into the similitude equations presented in Chapter 2:

P = 52.4 MPa

E = 884 m-kPa

I = 57.5 kPa-s

θ = 0.84 ms

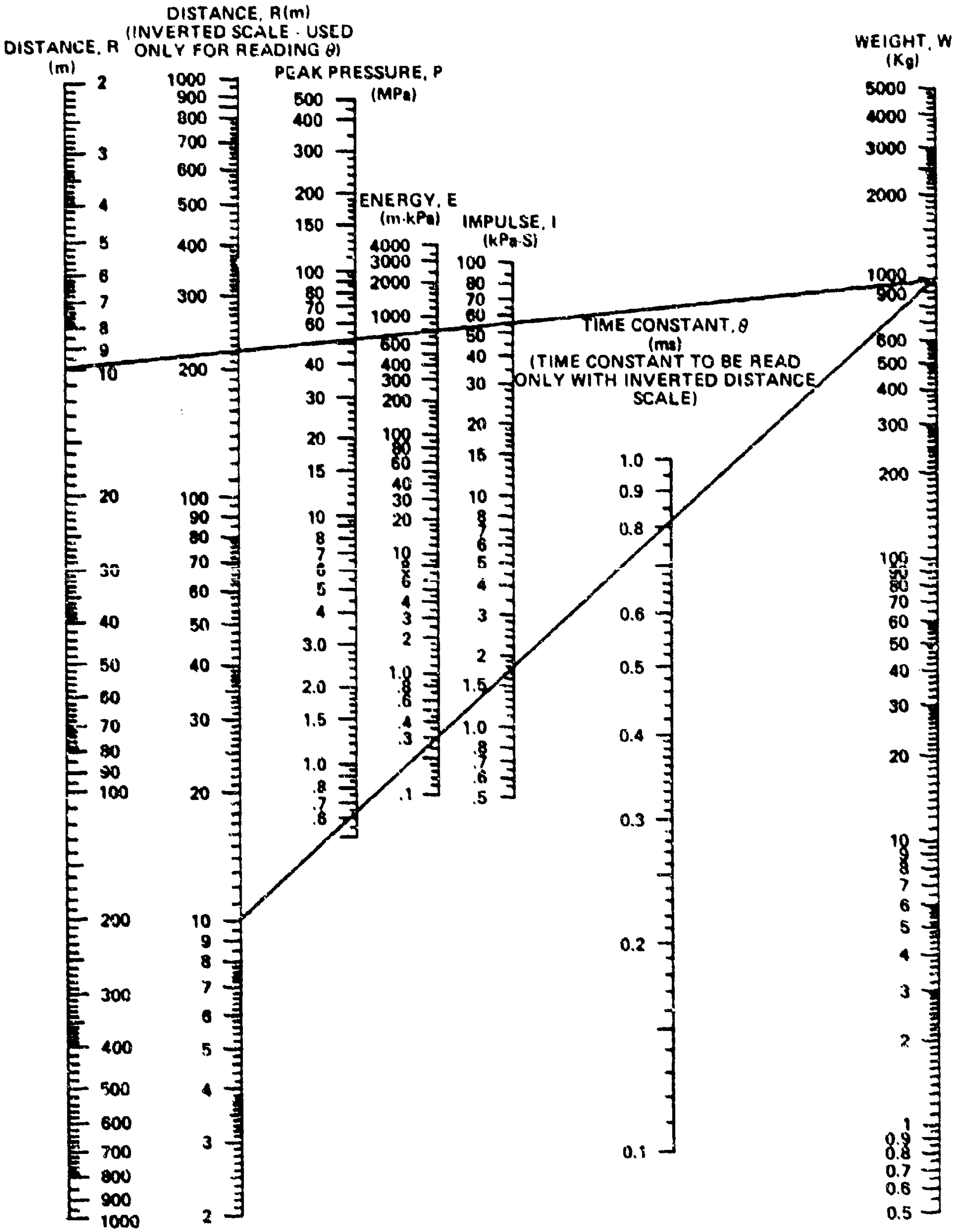


FIG. 3 UNDERWATER SHOCK WAVE PARAMETERS FROM A TNT CHARGE

TABLE 3-1 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETERS FOR 1 KILOGRAM OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa-SEC)	ENERGY (m-kPa)
135	0.44	0.069	12.04	459.01
130	0.45	0.070	11.69	429.03
125	0.47	0.070	11.34	239.96
120	0.48	0.071	10.98	371.78
115	0.50	0.072	10.62	344.52
110	0.52	0.072	10.26	318.17
105	0.54	0.073	9.89	292.76
100	0.57	0.074	9.52	268.28
95	0.59	0.074	9.16	244.75
90	0.62	0.075	8.77	222.18
85	0.65	0.076	8.39	200.58
80	0.69	0.077	8.00	179.96
75	0.73	0.078	7.61	160.33
70	0.78	0.079	7.21	141.71
65	0.83	0.080	6.80	124.11
60	0.89	0.082	6.39	107.55
55	0.96	0.083	5.97	92.04
50	1.04	0.085	5.54	77.61
45	1.14	0.087	5.11	64.27
40	1.27	0.089	4.66	52.06
35	1.42	0.091	4.20	40.99
30	1.63	0.094	3.72	31.11
25	1.91	0.098	3.23	22.45
20	2.33	0.102	2.71	15.06
15	3.00	0.108	2.17	9.00
10	4.28	0.117	1.58	4.36
5	7.85	0.135	0.92	1.26

TABLE 3-2 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETERS FOR 2 KILOGRAMS OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa-SEC)	ENERGY (m-kPa)
135	0.55	0.087	15.17	578.31
130	0.57	0.088	14.73	540.55
125	0.59	0.089	14.28	503.91
120	0.61	0.090	13.83	468.41
115	0.63	0.090	13.38	434.06
110	0.66	0.091	12.93	400.87
105	0.68	0.092	12.46	368.85
100	0.71	0.093	12.00	338.01
95	0.75	0.094	11.53	308.37
90	0.78	0.095	11.05	279.93
85	0.82	0.096	10.57	252.72
80	0.87	0.097	10.08	226.73
75	0.92	0.098	9.58	202.00
70	0.98	0.100	9.08	178.54
65	1.04	0.101	8.57	156.37
60	1.12	0.103	8.05	135.50
55	1.21	0.105	7.52	115.96
50	1.31	0.107	6.98	97.78
45	1.44	0.109	6.43	80.98
40	1.60	0.112	5.87	65.59
35	1.80	0.115	5.29	51.65
30	2.05	0.118	4.69	39.20
25	2.41	0.123	4.07	28.29
20	2.93	0.129	3.42	18.97
15	3.77	0.136	2.73	11.34
10	5.39	0.148	1.99	5.49
5	9.89	0.170	1.16	1.59

TABLE 3-3 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETRS FOR 5 KILOGRAMS OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa-SEC)	ENERGY (m-kPa)
135	0.75	0.119	20.58	784.39
130	0.77	0.120	19.99	733.64
125	0.80	0.121	19.38	683.91
120	0.83	0.122	18.78	635.73
115	0.86	0.123	18.16	589.11
110	0.89	0.124	17.54	544.07
105	0.93	0.125	16.92	500.61
100	0.97	0.126	16.28	458.76
95	1.01	0.127	15.65	418.52
90	1.06	0.129	15.00	379.93
85	1.12	0.130	14.34	342.99
80	1.18	0.132	13.68	307.73
75	1.25	0.134	13.01	274.16
70	1.33	0.135	12.33	242.32
65	1.42	0.138	11.63	212.22
60	1.52	0.140	10.93	183.90
55	1.64	0.142	10.21	157.39
50	1.78	0.145	9.48	132.71
45	1.95	0.148	8.73	109.90
40	2.17	0.152	7.96	89.02
35	2.44	0.156	7.18	70.10
30	2.79	0.161	6.36	53.20
25	3.27	0.167	5.52	38.39
20	3.98	0.174	4.64	25.75
15	5.12	0.185	3.70	15.3[illegible]
10	7.31	0.201	2.70	7.45
5	13.43	0.231	1.57	2.16

TABLE 3-4 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETERS FOR 8 KILOGRAMS OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa-SEC)	ENERGY (m-kPa)
135	0.87	0.139	24.09	918.02
130	0.90	0.140	23.38	858.07
125	0.93	0.141	22.67	799.91
120	0.97	0.142	21.96	743.56
115	1.00	0.143	21.24	689.03
110	1.04	0.145	20.52	636.35
105	1.09	0.146	19.79	585.52
100	1.13	0.147	19.05	536.56
95	1.19	0.149	18.30	489.51
90	1.24	0.151	17.54	444.37
85	1.31	0.152	16.78	401.16
80	1.38	0.154	16.00	359.92
75	1.46	0.156	15.22	320.66
70	1.55	0.158	14.42	283.42
65	1.66	0.161	13.61	244.22
60	1.78	0.163	12.78	215.09
55	1.92	0.166	11.94	184.08
50	2.08	0.170	11.09	155.22
45	2.29	0.173	10.21	128.54
40	2.53	0.177	9.31	104.12
35	2.85	0.182	8.39	81.99
30	3.26	0.188	7.44	62.22
25	3.83	0.195	6.45	44.90
20	4.66	0.204	5.42	30.12
15	5.99	0.216	4.33	18.00
10	8.55	0.235	3.16	8.[illegible]1
5	15.71	0.270	1.84	2.52

TABLE 3-5 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETERS FOR 20 KILOGRAMS OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa·SEC)	ENERGY (m·kPa)
135	1.18	0.188	32.67	1245.94
130	1.22	0.190	31.73	1164.57
125	1.27	0.191	30.77	1085.64
120	1.31	0.193	29.80	1009.16
115	1.36	0.195	28.83	935.16
110	1.42	0.196	27.85	863.65
105	1.48	0.198	26.85	794.67
100	1.54	0.200	25.85	728.23
95	1.61	0.202	24.84	664.36
90	1.69	0.204	23.81	603.10
85	1.78	0.207	22.77	544.46
80	1.87	0.209	21.72	488.48
75	1.98	0.212	20.65	435.20
70	2.11	0.215	19.57	384.66
65	2.25	0.218	18.47	336.89
60	2.41	0.222	17.35	291.93
55	2.60	0.226	16.21	249.84
50	2.83	0.230	15.05	210.66
45	3.10	0.235	13.86	174.46
40	3.44	0.241	12.64	141.31
35	3.87	0.247	11.39	111.27
30	4.43	0.255	10.10	84.45
25	5.20	0.265	8.76	60.94
20	6.32	0.277	7.36	40.88
15	8.13	0.293	5.88	24.43
10	11.61	0.318	4.28	11.82
5	21.32	0.366	2.49	3.42

TABLE 3-6 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETERS FOR 27 KILOGRAMS OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa-SEC)	ENERGY (m-kPa)
135	1.31	0.208	36.11	1377.03
130	1.35	0.210	35.06	1287.10
125	1.40	0.211	34.01	1199.86
120	1.45	0.213	32.94	1115.34
115	1.51	0.215	31.86	1033.55
110	1.57	0.217	30.78	954.52
105	1.63	0.219	29.68	878.28
100	1.70	0.221	28.57	804.85
95	1.78	0.223	27.45	734.26
90	1.87	0.226	26.31	666.55
85	1.96	0.229	25.17	601.74
80	2.07	0.231	24.00	539.88
75	2.19	0.234	22.82	480.99
70	2.33	0.238	21.63	425.13
65	2.48	0.241	20.41	372.33
60	2.66	0.245	19.17	322.64
55	2.88	0.250	17.91	276.12
50	3.13	0.254	16.63	232.82
45	3.43	0.260	15.32	192.82
40	3.80	0.266	13.97	156.17
35	4.27	0.273	12.59	122.98
30	4.89	0282	11.16	93.33
25	5.74	0.293	9.68	67.35
20	6.98	0.306	8.13	45.18
15	8.99	0.324	6.50	27.00
10	12.83	0.352	4.73	13.07
5	23.56	0.405	2.76	3.78

TABLE 3-7 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETERS FOR 50 KILOGRAMS OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa-SEC)	ENERGY (m-kPa)
135	1.61	0.256	44.35	1691.00
130	1.66	0.258	43.06	1580.57
125	1.72	0.260	41.76	1473.44
120	1.78	0.262	40.45	1369.64
115	1.85	0.264	39.13	1269.21
110	1.92	0.266	37.79	1172.16
105	2.00	0.269	36.45	1078.53
100	2.09	0.272	35.08	988.36
95	2.19	0.274	33.71	901.68
90	2.29	0.277	32.31	818.53
85	2.41	0.281	30.90	738.94
80	2.54	0.284	29.47	662.97
75	2.69	0.288	28.03	590.66
70	2.86	0.292	26.56	522.06
65	3.05	0.296	25.06	457.22
60	3.27	0.301	23.55	396.21
55	3.53	0.306	22.00	339.08
50	3.84	0.312	20.42	285.91
45	4.21	0.319	18.81	236.78
40	4.67	0.327	17.16	191.78
35	5.25	0.336	15.46	151.02
30	6.01	0.346	13.71	114.61
25	7.05	0.359	11.89	82.71
20	8.58	0.376	9.99	55.48
15	11.04	0.398	7.98	33.16
10	15.75	0.432	5.81	16.05
5	28.93	0.497	3.38	4.64

TABLE 3-8 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETERS FOR 64 KILOGRAMS OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa-SEC)	ENERGY (m-kPa)
135	1.74	0.278	48.15	1836.03
130	1.80	0.280	46.75	1716.13
125	1.87	0.282	45.34	1599.81
120	1.93	0.284	43.92	1487.11
115	2.01	0.287	42.48	1378.06
110	2.09	0.289	41.04	1272.69
105	2.17	0.292	39.57	1171.03
100	2.27	0.295	38.09	1073.13
95	2.37	0.298	36.60	979.01
90	2.49	0.301	35.09	888.73
85	2.62	0.305	33.55	802.32
80	2.76	0.309	32.00	719.84
75	2.92	0.313	30.43	641.32
70	3.10	0.317	28.83	566.84
65	3.31	0.322	27.21	496.44
60	3.55	0.327	25.57	430.19
55	3.83	0.333	23.89	368.16
50	4.17	0.339	22.17	213.43
45	4.57	0.346	20.42	257.09
40	5.07	0.355	18.63	208.23
35	5.70	0.365	16.78	163.97
30	6.52	0.376	14.88	124.44
25	7.66	0.390	12.91	89.80
20	9.31	0.408	10.84	60.24
15	11.98	0.432	8.66	36.00
10	17.10	0.469	6.31	17.43
5	31.41	0.540	3.67	5.04

TABLE 3-9 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETERS FOR 81 KILOGRAMS OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa-SEC)	ENERGY (m-kPa)
135	1.89	0.300	52.08	1986.01
130	1.95	0.303	50.57	1856.32
125	2.02	0.305	49.05	1730.50
120	2.09	0.307	47.51	1608.59
115	2.17	0.310	45.96	1490.63
110	2.26	0.313	44.39	1376.65
105	2.35	0.316	42.80	1266.69
100	2.45	0.319	41.20	1160.79
95	2.57	0.322	39.59	1058.99
90	2.69	0.326	37.95	961.33
85	2.83	0.330	36.29	867.86
80	2.99	0.334	34.62	778.64
75	3.16	0.338	32.92	693.71
70	3.36	0.343	31.19	613.14
65	3.58	0.348	29.44	536.99
60	3.84	0.354	27.65	465.33
55	4.15	0.360	25.84	398.23
50	4.51	0.367	23.98	335.79
45	4.94	0.375	22.09	278.09
40	5.48	0.384	20.15	225.24
35	6.16	0.394	18.16	177.37
30	7.06	0.407	16.10	134.61
25	8.28	0.422	13.96	97.14
20	10.07	0.441	11.73	65.16
15	12.96	0.468	9.37	38.94
10	18.50	0.508	6.83	18.85
5	33.98	0.584	3.97	5.45

TABLE 3-10 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETERS FOR 100 KILOGRAMS OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa-SEC)	ENERGY (m-kPa)
135	2.02	0.322	55.87	2130.53
130	2.09	0.325	54.25	1991.39
125	2.16	0.327	52.62	1856.42
120	2.24	0.330	50.96	1725.64
115	2.33	0.333	49.30	1599.10
110	2.42	0.336	47.62	1476.83
105	2.52	0.339	45.92	1358.86
100	2.63	0.342	44.20	1245.26
95	2.75	0.346	42.47	1136.04
90	2.89	0.350	40.71	1031.28
85	3.04	0.354	38.94	931.01
80	3.20	0.358	37.14	835.30
75	3.39	0.363	35.31	744.19
70	3.60	0.368	33.46	657.76
[illegible]	3.84	0.373	31.58	576.07
60	4.12	0.379	29.67	499.19
55	4.45	0.386	27.72	427.21
50	4.84	0.394	25.73	360.22
[illegible]	5.30	0.402	23.70	298.33
40	5.88	0.412	21.62	241.63
35	6.61	0.423	19.48	190.27
30	7.57	0.436	17.27	144.40
25	8.88	0.453	14.98	104.20
20	10.80	0.474	12.58	69.90
15	13.91	0.502	10.05	41.77
10	19.85	0.545	7.32	20.22
5	36.45	0.620	4.26	5.85

TABLE 3-11 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETERS FOR 125 KILOGRAMS OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa·SEC)	ENERGY (m·kPa)
135	2.18	0.347	60.19	2295.04
130	2.25	0.350	58.44	2145.16
125	2.33	0.352	56.68	1999.77
120	2.42	0.355	54.90	1858.89
115	2.51	0.358	53.11	1722.58
110	2.61	0.362	51.29	1590.86
105	2.72	0.365	49.47	1463.79
100	2.84	0.369	47.62	1341.41
95	2.97	0.372	45.75	1223.77
90	3.11	0.377	43.86	1110.91
85	3.27	0.381	41.94	1002.90
80	3.45	0.386	40.00	899.80
75	3.65	0.391	38.04	801.65
70	3.88	0.396	36.04	708.55
65	4.14	0.402	34.02	620.55
60	4.44	0.409	31.96	537.74
55	4.79	0.416	29.86	460.20
50	5.21	0.424	27.72	388.04
45	5.71	0.433	25.53	321.36
40	6.34	0.444	23.29	260.29
35	7.12	0.456	20.98	204.97
30	8.16	0.470	18.60	155.55
25	9.57	0.488	16.13	112.25
20	11.64	0.510	13.56	75.30
15	14.98	0.541	10.83	43.00
10	21.38	0.587	7.89	21.78
5	39.27	0.675	4.59	6.30

TABLE 3-12 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETERS FOR 216 KILOGRAMS OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa-SEC)	ENERGY (m-kPa)
135	2.62	0.416	72.23	2754.05
130	2.70	0.420	70.13	2574.20
125	2.80	0.423	68.01	2399.72
120	2.90	0.426	65.88	2230.67
115	3.01	0.430	63.73	2067.09
110	3.13	0.434	61.55	1909.04
105	3.26	0.438	59.36	1756.55
100	3.40	0.442	57.14	1609.69
95	3.56	0.447	54.90	1468.52
90	3.73	0.452	52.63	1333.10
85	3.93	0.457	50.33	1203.48
80	4.14	0.463	48.00	1079.75
75	4.38	0.469	45.65	961.99
70	4.65	0.475	43.25	850.26
65	4.97	0.483	40.82	744.66
60	5.33	0.490	38.35	645.28
55	5.75	0.499	35.83	552.24
50	6.25	0.509	33.26	465.65
45	6.86	0.520	30.63	385.63
40	7.60	0.532	27.94	312.35
35	8.55	0.547	25.19	245.96
30	9.79	0.564	22.32	186.67
25	11.48	0.585	19.36	134.70
20	13.97	0.612	16.26	90.36
15	17.98	0.649	12.99	54.00
10	25.65	0.704	9.47	26.14
5	47.12	0.810	5.51	7.56

TABLE 3-13 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETERS FOR 343 KILOGRAMS OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa-SEC)	ENERGY (m-kPa)
135	3.05	0.486	84.26	3213.06
130	3.15	0.490	81.82	3003.23
125	3.27	0.493	79.35	2799.68
120	3.38	0.497	76.86	2602.45
115	3.51	0.502	74.35	2411.61
110	3.65	0.506	71.81	2227.21
105	3.80	0.511	69.25	2049.31
100	3.97	0.516	66.66	1877.97
95	4.15	0.521	64.05	1713.27
90	4.36	0.527	61.40	1555.28
85	4.58	0.533	58.72	1404.06
80	4.83	0.540	56.00	1259.71
75	5.11	0.547	53.25	1122.32
70	5.43	0.555	50.46	991.97
65	5.79	0.563	47.62	868.77
60	6.22	0.572	44.74	752.83
55	6.71	0.582	41.80	644.28
50	7.29	0.594	38.80	543.26
45	8.00	0.606	35.74	449.91
40	8.87	0.621	32.60	364.41
35	9.97	0.638	29.37	286.95
30	11.42	0.658	26.04	217.78
25	13.40	0.683	22.59	157.15
20	16.29	0.714	18.98	105.41
15	20.97	0.757	15.16	63.00
10	29.93	0.821	11.05	30.49
5	54.97	0.945	6.43	8.82

TABLE 3-14 VALUES OF THE UNDERWATER SHOCK WAVE PARAMETERS FOR 512 KILOGRAMS OF TNT

PRESSURE (MEGAPASCALS)	DISTANCE (METERS)	TIME CONSTANT (MILLISECONDS)	IMPULSE (kPa-SEC)	ENERGY (m-kPa)
135	3.49	0.555	96.30	3672.07
130	3.61	0.559	93.50	3432.26
125	3.73	0.564	90.68	3199.63
120	3.87	0.569	87.84	2974.23
115	4.01	0.573	84.97	2756.12
110	4.17	0.579	82.07	2545.38
105	4.35	0.584	79.14	2342.07
100	4.54	0.590	76.19	2146.26
95	4.75	0.596	73.20	1958.03
90	4.98	0.603	70.17	1777.46
85	5.23	0.610	67.11	1604.64
80	5.52	0.617	64.01	1439.67
75	5.84	0.625	60.86	1282.65
70	6.21	0.634	57.67	1133.68
65	6.62	0.643	54.43	992.88
60	7.10	0.654	51.13	860.38
55	7.67	0.665	47.77	736.32
50	8.34	0.678	44.35	620.86
45	9.14	0.693	40.84	514.18
40	10.14	0.710	37.26	416.47
35	11.40	0.729	33.57	327.95
30	13.05	0.752	29.76	248.89
25	15.31	0.780	25.81	179.60
20	18.62	0.816	21.69	120.47
15	23.97	0.865	17.32	72.00
10	34.20	0.939	12.62	34.85
5	62.83	1.080	7.35	10.08

CHAPTER 4. SHOCK WAVE CONVERSION FACTORS

This chapter presents a comparison of the underwater performance of many high explosives. Table 4-1 presents Equal Weight Ratios (See Chapter 1 for definitions of Equal Weight and Equivalent Weight Ratios) for several explosives -- based on charges weighing more than 20 kilograms. Tables 4-2 and 4-3 present Equivalent Weight Ratios based on shock wave energy and relative bubble energies for a wide series of explosives (Tables 4-2 and 4-3 are based on small charges with weights less than 0.5 kilograms).

The Equal Weight Ratios presented in Table 4-1 can be used in conjunction with the information presented in Chapter 3 on the values of the TNT parameters to estimate the parameters for other explosives. This is done by simply multiplying the parameter of interest (for a given charge size) by the appropriate Equal Weight Ratio.

CAVEATS:

For a given series of underwater explosion tests, the shock wave parameters relative to a standard explosive are determined from lines fitted to the data by the method of least squares. Hence, the slopes of the similitude lines reported in the various references cited in Chapter 2 vary somewhat. The Equal Weight Ratios presented in Table 4-1 assume a constant slope for all explosives for each of the four parameters. This seems to be a reasonable assumption for most explosives and should give shock wave parameter estimates which fall within the normal scatter. Reference 4-1 presents the exact equations for determining equal weight ratios. The possible exceptions are explosives of the perchlorate type which seem to produce shock waves with greater time constants and similitude equations with smaller weight exponents than other explosive compositions.

The charges used to obtain the values shown in Tables 4-2 and 4-3 were all squat cylinders weighing about 0.5 kilograms. Shock wave energy is calculated from diaphragm gages at a distance of about 1 meter and facing the side of the charge. The precision of the measurements are $\pm$ 0.03 for W_{Dd} and $\pm$ 0.05 for RBE.

4-1 "Analysis and Correlation of Underwater Explosion Data at NOL," Phillips, D. E., NOLTR 69-192, January 1970.

PROBLEM EXAMPLE 1:

Using the Equal Weight Ratios presented in Table 4-1, determine the peak pressure, time constant, impulse, and energy 3.04 meters from a 100 kilogram charge of H-6.

SOLUTION:

(1) From Table 4-1, the Equal Weight Ratios for H-6, relative to TNT are:

P -- 1.13 $\quad\quad$ θ -- 1.05

I -- 1.14 $\quad\quad$ E -- 1.37

(2) From Table 3-10, at a distance of 3.04 meters from 100 kilograms of TNT, the following are the values of the shock wave parameters:

$P = 85$ MPa

$\theta = 0.354$ msec

$I = 38.94$ kPa-s

$E = 931.01$ m-kPa

(3) To obtain the parameters for H-6, simply multiply the TNT parameter by the appropriate equal weight ratio. Thus at 3.04 meters from 100 kg of H-6:

$P = 85 \times 1.13 = 96.1$ MPa

$\theta = 0.354 \times 1.05 = 0.372$ ms

$I = 38.94 \times 1.14 = 44.39$ kPa-s

$E = 931.01 \times 1.37 = 1275.48$ m-kPa $= 1.275$ m-MPa

PROBLEM EXAMPLE 2:

What is the equivalent weight of RDX for shock wave energy using HBX-1 as a standard, rather than pentolite?

SOLUTION:

(1) From Table 4-2, 1 kilogram of RDX is equivalent to 1.10 kilograms of pentolite and 1 kilogram of HBX-1 is equivalent to 1.13 kilograms of pentolite.

(2) $$\frac{1 \text{ kg RDX}}{1 \text{ kg HBX-1}} = \frac{1.10 \text{ kg pentolite}}{1.13 \text{ kg pentolite}}$$

(3) 1 kg RDX = 0.97 kg HBX-1

(4) $(W_{Dd})_{\text{HBX-1}} = 0.97$ for RDX

TABLE 4-1 SHOCK WAVE AND BUBBLE CONVERSION FACTORS

EXPLOSIVE	EQUAL WEIGHT RATIO D_{Wd} (RELATIVE TO HBX-1)				EQUAL WEIGHT RATIO D_{Wd} (RELATIVE TO TNT)				$(RBE)_{TNT}$	$(RPBE)_{TNT}$
	P_m	θ	I	E	P_m	θ	I	E		
HBX-1	1.00	1.00	1.00	1.00	1.08	0.99	1.12	1.26	1.48	1.44
TNT	0.92	1.01	0.90	0.79	1.00	1.00	1.00	1.00	1.00	1.00
HBX-3	0.89	1.10	0.99	0.86	0.96	1.08	1.10	1.08	1.33	1.32
H-6	1.04	1.06	1.02	1.09	1.13	1.05	1.14	1.37	1.69	1.59
PENTOLITE	1.00	1.01	0.89	0.87	1.08	1.00	1.00	1.09	1.00	1.02

TABLE 4-2 UNDERWATER SHOCK WAVE AND BUBBLE ENERGY EQUIVALENT WEIGHT RATIOS FOR SEVERAL UNDERWATER EXPLOSIVES

MATERIAL	SHOCK WAVE $(W_{DW})_{pent}$	BUBBLE $(RBE)_{pent}$
HMX	1.11	1.06
RDX	1.10	1.02
TNT	0.84	0.94
PETN	1.15	1.13
TETRYL	1.00	0.98
TNETB	1.18	1.16
H-6	1.18	1.54
HBX-1	1.13	1.47
HBX-3	1.00	1.95
PENTOLITE	1.00	1.00

NOTE: BASED ON SMALL CHARGES OF WEIGHT ABOUT 0.5 KILOGRAMS

CAVEAT: THESE PARAMETERS MAY BE INFLUENCED BY CHARGE DENSITY. SEE CHAPTER 21 FOR THESE EFFECTS

TABLE 4-3 UNDERWATER SHOCK WAVE AND BUBBLE ENERGY EQUIVALENT WEIGHT RATIOS FOR MULTI-COMPONENT HIGH EXPLOSIVES

COMPOSITION								
%RDX	%TNT	%TNETB	%BTNEU	%PETN	%Al	%WAX	SHOCK WAVE $(W_{Dd})_{pent}$	BUBBLE $(RBE)_{pent}$
25.0	75.0	0.0	0.0	0.0	0.0	0.0	0.91**	0.96**
40.0	60.0	0.0	0.0	0.0	0.0	0.0	0.94**	0.97**
50.0	50.0	0.0	0.0	0.0	0.0	0.0	0.97**	0.98**
60.0	40.0	0.0	0.0	0.0	0.0	0.0	1.02	1.00
48.6	46.4	0.0	0.0	0.0	00.0	5.0	0.96	0.97
43.5	41.5	0.0	0.0	0.0	10.0	5.0	1.08	1.25
40.0	38.0	0.0	0.0	0.0	17.0	5.0	1.13	2.47
35.9	34.1	0.0	0.0	0.0	25.0	5.0	1.13	1.70
30.7	29.3	0.0	0.0	0.0	35.0	5.0	1.02	1.96
25.6	24.4	0.0	0.0	0.0	45.0	5.0	0.80	1.87
85.0	0.0	0.0	0.0	0.0	10.0	5.0	1.22	1.30
78.0	0.0	0.0	0.0	0.0	17.0	5.0	1.27	1.42
75.0	0.0	0.0	0.0	0.0	20.0	5.0	1.29	1.55
70.0	0.0	0.0	0.0	0.0	25.0	5.0	1.24	1.69
65.0	0.0	0.0	0.0	0.0	30.0	5.0	1.16	1.84
55.0	0.0	0.0	0.0	0.0	40.0	5.0	1.00	1.96
45.0	0.0	0.0	0.0	0.0	50.0	5.0	0.78	1.81
35.0	0.0	0.0	0.0	0.0	60.0	5.0	0.58	1.56
25.0	0.0	0.0	0.0	0.0	70.0	5.0	0.37	1.13
90.0	0.0	0.0	0.0	0.0	10.0	0.0	1.25	1.22
83.0	0.0	0.0	0.0	0.0	17.0	0.0	1.32	1.46
80.0	0.0	0.0	0.0	0.0	20.0	0.0	1.32**	1.60**
75.0	0.0	0.0	0.0	0.0	25.0	0.0	1.32	1.74
70.0	0.0	0.0	0.0	0.0	30.0	0.0	1.26	1.86
60.0	0.0	0.0	0.0	0.0	40.0	0.0	1.06	1.95
50.0	0.0	0.0	0.0	0.0	50.0	0.0	0.79	2.10
40.0	0.0	0.0	0.0	0.0	60.0	0.0	0.51	2.13
30.0	0.0	0.0	0.0	0.0	70.0	0.0	0.28	1.98
70.0	0.0	0.0	0.0	0.0	0.0	30.0	0.75	0.86
75.0	0.0	0.0	0.0	0.0	0.0	25.0	0.84	0.95
85.0	0.0	0.0	0.0	0.0	0.0	15.0	0.97	0.98
95.0	0.0	0.0	0.0	0.0	0.0	5.0	1.04	1.02
97.0	0.0	0.0	0.0	0.0	0.0	3.0	1.06**	1.02**

** INTERPOLATED VALUES

NOTE: BASED ON SMALL CHARGES OF WEIGHT ABOUT 0.5 KILOGRAMS

TABLE 4-3 (CONTINUED)

COMPOSITION								
%RDX	%TNT	%TNETB	%BTNEU	%PETN	%Al	%WAX	SHOCK WAVE $(W_{Dd})_{psnt}$	BUBBLE $(RBE)_{pent}$
66.0	0.0	17.0	0.0	0.0	17.0	0.0	1.34	1.62
42.0	0.0	28.0	0.0	0.0	30.0	0.0	1.27	1.96
10.0	0.0	60.0	0.0	0.0	30.0	0.0	1.29	1.98
20.0	0.0	40.0	0.0	0.0	40.0	0.0	1.09	2.17
10.0	0.0	40.0	0.0	0.0	50.0	0.0	0.78	2.28
0.0	0.0	90.0	0.0	0.0	10.0	0.0	1.24	1.33
0.0	0.0	83.0	0.0	0.0	17.0	0.0	1.31	1.63
0.0	0.0	80.0	0.0	0.0	20.0	0.0	1.32**	1.79**
0.0	0.0	75.0	0.0	0.0	25.0	0.0	1.33	1.94
0.0	0.0	70.0	0.0	0.0	30.0	0.0	1.30	2.00
0.0	0.0	65.0	0.0	0.0	35.0	0.0	1.23**	2.06**
0.0	0.0	60.0	0.0	0.0	40.0	0.0	1.05	2.22
0.0	0.0	50.0	0.0	0.0	50.0	0.0	0.78	2.29
0.0	0.0	40.0	0.0	0.0	60.0	0.0	0.51	2.30
0.0	0.0	30.0	0.0	0.0	70.0	0.0	0.21	2.21
0.0	46.0	0.0	49.0	0.0	00.0	5.0	0.94	0.98
0.0	38.0	0.0	40.0	0.0	17.0	5.0	1.15	1.42
0.0	34.0	0.0	36.0	0.0	25.0	5.0	1.12	1.69
0.0	31.5	0.0	33.5	0.0	30.0	5.0	1.08	1.79
0.0	29.0	0.0	31.0	0.0	35 0	5.0	1.01	1.82
0.0	26.5	0.0	28.5	0.0	40.0	5.0	0.90	1.90
0.0	24.5	0.0	25.5	0.0	45.0	5.0	0.79	1.92
0.0	22.0	0.0	23.0	0.0	50.0	5.0	0.68	1.88
0.0	0.0	0.0	0.0	90.0	10.0	0.0	1.32	1.42
0.0	0.0	0.0	0.0	80.0	20.0	0.0	1.41	1.76
0.0	0.0	0.0	0.0	70.0	30.0	0.0	1.43	1.95
0.0	0.0	0.0	0.0	60.0	40.0	0.0	1.22	2.13
0.0	0.0	0.0	0.0	50.0	50.0	0.0	0.91	2.17
0.0	0.0	0.0	0.0	40.0	60.0	0.0	0.56	2.36

** INTERPOLATED VALUES

NOTE: BASED ON SMALL CHARGES OF WEIGHT ABOUT 0.5 KILOGRAMS

CHAPTER 5. PRESSURE-PULSE CHARACTERISTICS OF DEEP TNT EXPLOSIONS

This chapter presents the pressure-pulse characteristics of deep TNT explosions. The information was obtained from charges fired at scaled depths (depth/charge weight$^{1/3}$) between 60 and 5500 meters/kilogram$^{1/3}$. The figure below shows the nomenclature used to describe the pressure-pulse characteristics. Note that the divisions after the shock front are arbitrary and are used simply for the convenience of measurement.

Table 5-1 presents definitions of the symbols used in this chapter.

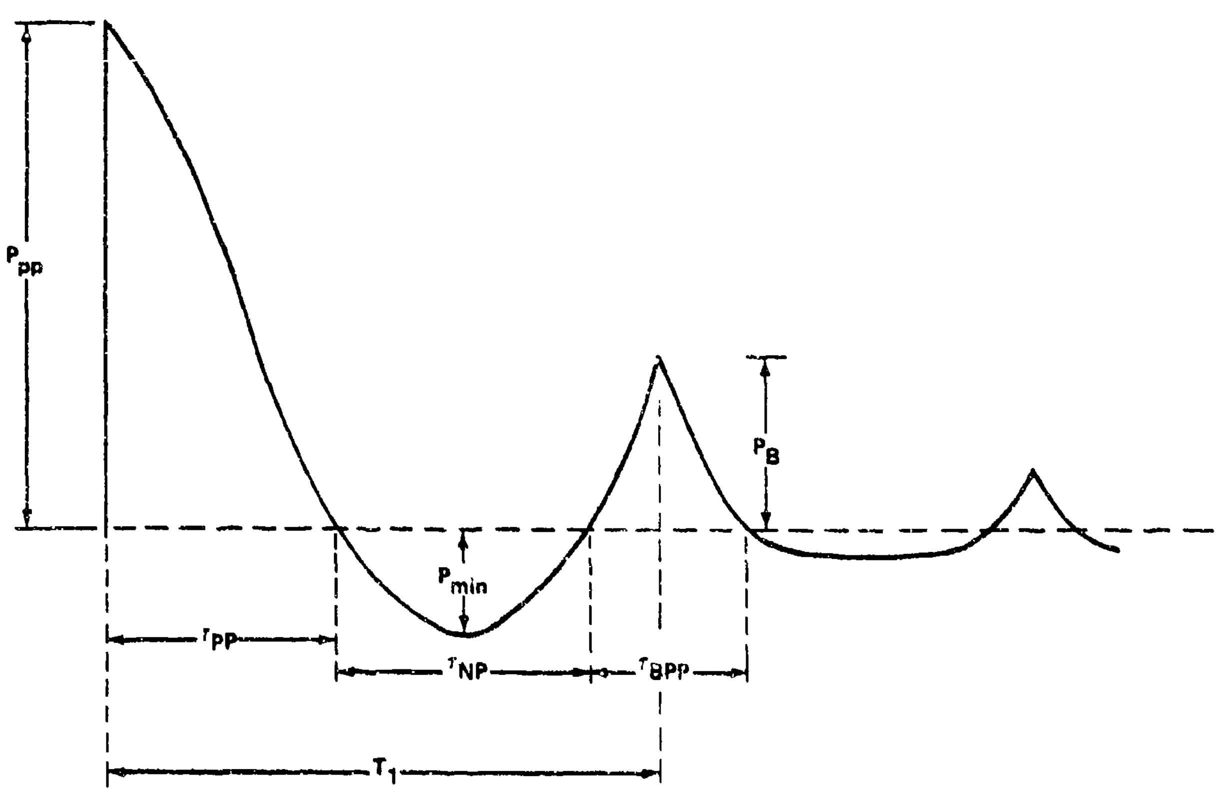


FIG. 5-1 PRESSURE-PULSE CHARACTERISTICS OF DEEP EXPLOSIONS

CAVEATS:

(1) The data are based on a limited number of shots, with only one or two channels of useable information recorded on each shot.

(2) The experimental set-up was such that the data were recorded directly above the charge -- thus, off-axis pulse characteristics should only be inferred from these data.

(3) In summary, the data presented here are the best available, but because of the small number of experiments and the experimental set-up, these prediction techniques are, at best, approximations.

PROBLEM EXAMPLE:

Within the limitations presented above (see Caveats), describe the pressure pulse characteristics produced at a range of 2 kilometers from a 1000 kilogram charge of TNT detonating at a depth of 3000 meters.

SOLUTION:

(1) $W = 1000$ kg, $W^{1/3} = 10.0\ kg^{1/3}$

(2) $R = 2000$ meters; $R/W^{1/3} = 2000/10 = 200\ m/kg^{1/3}$

(3) Z_o = Charge Depth + 10 = 3000 + 10 = 3010 meters

(4) $P_{pp} = (50.4)(3010)^0(200)^{-1.13}$

$P_{pp} = 0.1266$ MPa = 126.6 kPa

(5) $P_B = (2.917)(3010)^{1/6}(200)^{-1}$

$P_B = 0.0554$ MPA = 55.4 kPa

(6) $P_{min} = (-312.9)(3010)^{1/3}(200)^{-1}$

$P_{min} = -22.59$ kPa

(7) $I_{pp}/W^{1/3} = (36.2)(3010)^{1/3}(200)^{-0.97}$

$I_{pp}/W^{1/3} = 0.0147\ kPa\text{-}s/kg^{1/3}$

$I_{pp} = (0.0147)(10) = 0.147$ kPa-s

(8) $I_B/W^{1/3} = (85.2)(3010)^{-0.4}(200)^{-1}$

$I_B/W^{1/3} = 0.0173\ kPa\text{-}s/kg^{1/3}$

$I_B = (0.0173)(10) = 0.173$ kPa-s

(9) $E_{pp}/W^{1/3} = (214.9)(3010)^{-0.2}(200)^{-2.07}$

$E_{pp}/W^{1/3} = 0.00074712\ m\text{-}kPa/kg^{1/3}$

$E_{pp} = (0.00074712)(10) = 0.007471$ m-kPa

(10) $\tau_{pp}/W^{1/3} = (0.0117)(3010)^{-0.4}(200)^0$

$\tau_{pp}/W^{1/3} = 0.00048\ sec/kg^{1/3}$

$\tau_{pp} = (0.00048)(10) = 0.0048$ sec = 4.8 ms

(11) $\tau_{np}/W^{1/3} = (1.499)(3010)^{-5/6}(200)^0$

$\tau_{np}/W^{1/3} = 0.0019\ s/kg^{1/3}$

$\tau_{np} = (0.0019)(10) = 0.019$ s = 19 ms

(12) $\tau_{bpp}/W^{1/3} = (0.532)(3010)^{-5/6}(200)^0$

$\tau_{bpp}/W^{1/3} = 0.000672\ s/kg^{1/3}$

$\tau_{bpp} = (0.000672)(10) = 0.00672$ s = 6.72 ms

(13) $T_1/W^{1/3} = (2.098)(3010)^{-5/6}(200)^0$

$T_1/W^{1/3} = 0.00265$ s/kg$^{1/3}$

$T_1 = (0.00265)(10) = 0.0265$ s $= 26.5$ ms

In summary:

$P_{pp} = 126.6$ kPa

$P_B = 55.4$ kPa

$P_{min} = -22.59$ kPa

$I_{pp} = 0.147$ kPa-s

$I_B = 0.173$ kPa-s

$E_{pp} = 0.00747$ m-kPa

$\tau_{pp} = 4.8$ ms

$\tau_{np} = 19$ ms

$\tau_{bpp} = 6.72$ ms

$T_1 = 26.5$ ms

The information in this chapter is from:

"Pressure Pulse Characteristics of Deep Explosions as a Function of Depth and Range," Slifko, J. P., NOLTR 67-87, September 1967.

TABLE 5-1 DEFINITION OF SYMBOLS

P_{pp}	PEAK PRESSURE OF THE FIRST POSITIVE PHASE (MPa)
P_B	MAXIMUM PRESSURE OF THE FIRST BUBBLE PULSE (MPa)
P_{min}	MINIMUM PRESSURE OF THE FIRST BUBBLE NEGATIVE PHASE (MPa)
τ_{pp}	POSITIVE PHASE DURATION (s)
τ_{np}	NEGATIVE PHASE DURATION (s)
τ_{bpp}	FIRST BUBBLE PHASE DURATION (s)
T_1	FIRST BUBBLE PERIOD (s)
I_{pp}	IMPULSE OF THE FIRST POSITIVE PHASE (kPa-s)
I_B	FIRST BUBBLE PULSE IMPULSE (kPa-s)
E_{pp}	ENERGY FLUX DENSITY OF THE FIRST POSITIVE PHASE (m-kPa)
Z_0	CHARGE DEPTH IN METERS +10
W	CHARGE WEIGHT (KILOGRAMS)
R	SLANT RANGE TO CHARGE (METERS)
k, α, β	LEAST SQUARES FIT CONSTANTS (COEFFICIENTS AND EXPONENTS)

TABLE 5-2 PRESSURE PULSE CHARACTERISTICS OF DEEP TNT EXPLOSIONS

THE PRESSURE PULSE CHARACTERISTICS ARE PRESENTED IN EQUATIONS OF THE FORM:

$$Y = k\,Z_0^{\alpha}\,(R/W^{1/3})^{\beta}$$

Y	k	α	β	LIMITS OF VARIABLE
P_{pp} (MPa)	50.4	0	−1.13	$5500>R/W^{1/3}>79$
P_B (MPa)	9.03	0	−1.00	$1219>Z_0>152$
P_B (MPa)	2.917	1/6	−1.00	$4572>Z_0>1219$
P_{min} (kPa)	−312.54	1/3	−1.00	$4267>Z_0>1372$
P_{min} (kPa)	− 28.987	2/3	−1.00	$1372>Z_0>152$
$I_{pp}/W^{1/3}$ (kPa-s/kg$^{1/3}$)	38.2	−1/3	−0.97	$5500>R/W^{1/3}>198$
$I_B/W^{1/3}$ (kPa-s/kg$^{1/3}$)	88.2	−2/5	−1.00	$3174>R/W^{1/3}>198$
$E_{pp}/W^{1/3}$ (m-kPa/kg$^{1/3}$)	214.9	−1/5	−2.07	$5500>R/W^{1/3}>198$
$\tau_{pp}/W^{1/3}$ (s/kg$^{1/3}$)	0.268	−5/6	0	$1372>Z_0>152$
$\tau_{pp}/W^{1/3}$ (s/kg$^{1/3}$)	0.0117	−2/5	0	$6706>Z_0>1372$
$\tau_{np}/W^{1/3}$ (s/kg$^{1/3}$)	1.499	−5/6	0	$4267>Z_0>198$
$\tau_{bpp}/W^{1/3}$ (s/kg$^{1/3}$)	0.532	−5/6	0	$1372>Z_0>198$
$\tau_{bpp}/W^{1/3}$ (s/kg$^{1/3}$)	0.099	−3/5	0	$6706>Z_0>1372$
$T_1/W^{1/3}$ (s/kg$^{1/3}$)	2.098	−5/6	0	$4267>Z_0>198$

CHAPTER 6. IMPULSE AND ENERGY RATIOS vs REDUCED TIME*

This chapter presents the ratio of the shock wave impulse and energy at a reduced time of t/θ to that which occurs at a time of 5θ (the "usual" integration limit). These curves are experimentally determined and appear to apply to any conventional high explosive.

PROBLEM EXAMPLE:

A shock wave has a time constant of 150 microseconds; at 450 microseconds after shock arrival, what fraction of the impulse and energy has already been obtained (as compared to the impulse and energy at 5θ)

SOLUTION:

(1) $t/\theta = 450/150 = 3.0$

(2) with this value of t/θ enter either Figure 6 or Table 6, and obtain the following:

$$I/I_{5\theta} = 0.825$$

$$E/E_{5\theta} = 0.950$$

(3) thus, at a $t/\theta = 3.0$, 82.5% of the impulse and 95.0% of the energy have been obtained.

*This information is from unpublished data of D. E. Phillips.

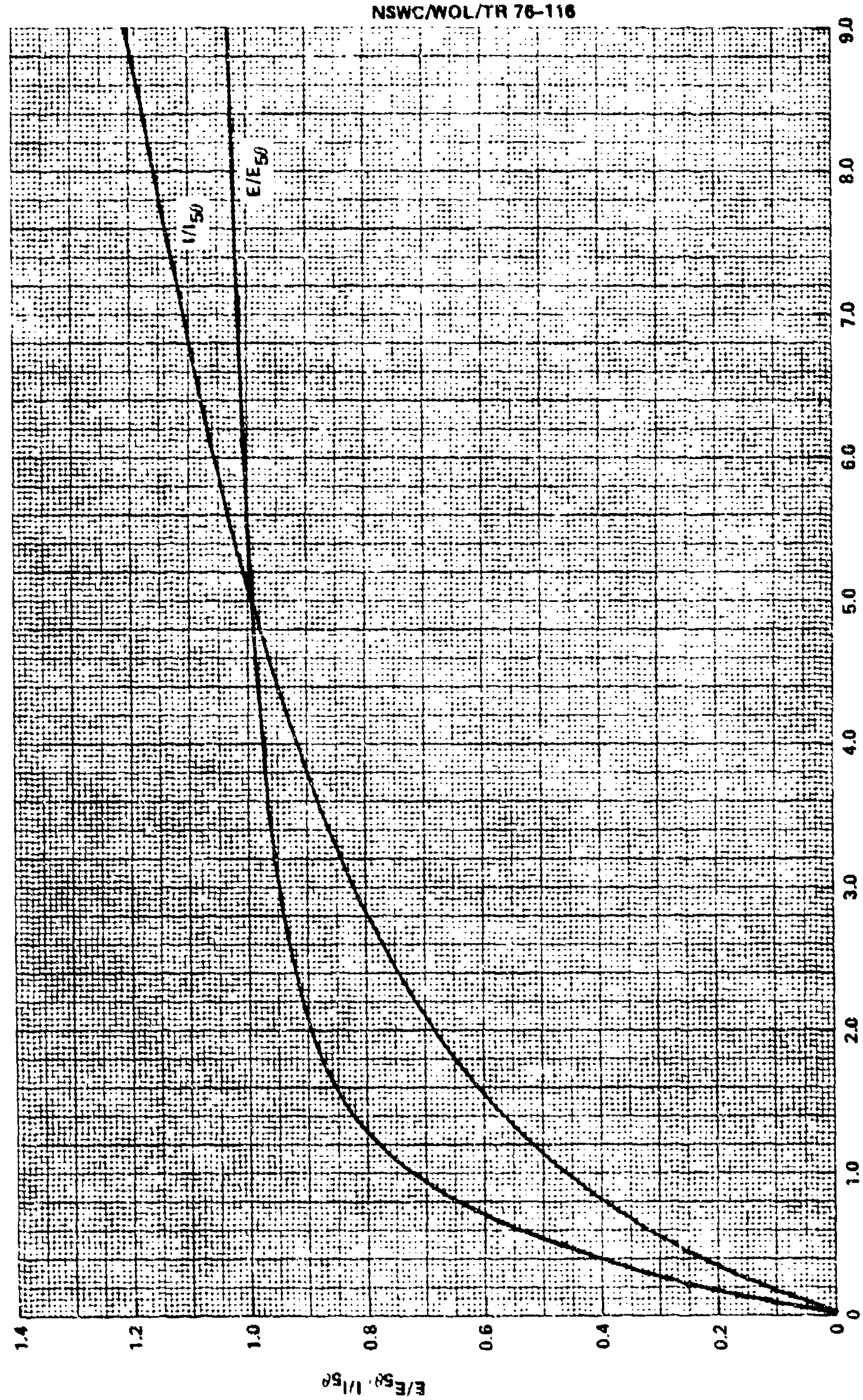


FIG. 6 SHOCK WAVE IMPULSE AND ENERGY RATIOS VS. REDUCED TIME

TABLE 6 SHOCK WAVE IMPULSE AND ENERGY RATIOS VS. REDUCED TIME

t/θ	$I/I_{5\theta}$	$E/E_{5\theta}$
0	0	0
0.2	0.120	0.250
0.4	0.230	0.415
0.6	0.320	0.540
0.8	0.400	0.650
1.0	0.465	0.725
1.2	0.525	0.763
1.4	575	0.825
1.6	0.620	0.555
1.8	0.660	0.880
2.0	0.690	0.900
2.2	0.720	0.915
2.4	0.750	0.925
2.6	0.775	0.935
2.8	0.800	0.945
3.0	0.825	0.950
3.2	0.845	0.960
3.4	0.865	0.965
3.6	0.885	0.970
3.8	0.900	0.975
4.0	0.920	0.980
4.2	0.935	0.983
4.4	0.955	0.987
4.6	0.970	0.990
4.8	0.980	0.995
5.0	1.000	1.000
5.2	1.010	1.002
5.4	1.020	1.004
5.6	1.035	1.006
5.8	1.045	1.008
6.0	1.060	1.010
6.2	1.070	1.012
6.4	1.080	1.014
6.6	1.095	1.016
6.8	1.105	1.018

TABLE 6 SHOCK WAVE IMPULSE AND ENERGY RATIOS
VS. REDUCED TIME (CONTINUED)

t/θ	$I/I_{5\theta}$	$E/E_{5\theta}$
7.0	1.115	1.020
7.2	1.125	1.022
7.4	1.135	1.024
7.6	1.145	1.026
7.8	1.155	1.028
8.0	1.165	1.030
8.2	1.175	1.032
8.4	1.185	1.034
8.6	1.195	1.036
8.8	1.205	1.038
9.0	1.210	1.040

CHAPTER 7. SURFACE CUTOFF

A shock wave moving in water will be reflected as a rarefaction wave when it encounters a second medium less dense than water, e.g., a water/air boundary. The rarefaction wave, generated by the reflection of the primary shock wave from the surface, propagates downward and relieves the pressure behind the primary shock wave. If the shock wave is treated as a weak (acoustic) wave, this interaction instantaneously decreases the pressure in the primary shock wave to a negative value, as shown by the broken line in Figure 7, Point A. Cavitation occurs in seawater when its pressure decreases to a value somewhat above its vapor pressure. The pressure of the primary shock wave is, therefore, reduced to a value which, is usually so close to ambient water pressure that the shock wave pulse appears to have been truncated, i.e., reduced to ambient pressure.

For a strong primary shock wave, the r lected rarefaction wave propagates into water that has already been set in motion by the wave. Therefore, the rarefaction wave actually arrives earlier than predicted from the acoustic approximation, which ignores the particle velocity, and the pressure cutoff is not instantaneous. This effect typically gives a pulse shape shown by the solid line for Point A of Figure 7. The shallower the point at which pressure measurements are made, the sooner the primary shock pulse is "cut off" and, hence the shorter its duration (See Figure 7 , Point B). At shallow enough locations, the rarefaction wave interacts with the shock front and reduces the peak pressure (See Figure 7 , Points C and D). The region in which the peak pressure is reduced is known as the "anomalous region".

The effects of surface reflection decrease rapidly with increased depth of either the explosion or the point of measurement. Conversely, as the depth of burst is decreased (or the yield increased for a given depth of burst), the effects increase. The size of the anomalous region increases with decreased depth of burst until, for a surface bur , the anomalous region includes all points beneath the water surface except those close to the explosion and directly under it.

Surface Cutoff Time (t_c) is defined as the time-of-arrival of the surface reflected rarefaction wave (in the acoustic approximation), following the direct shock wave arrival.

Surface Cutoff Time (t_c) can be determined from geometric considerations involving the locations of the charge and the gage. Two expressions for t_c are:

$$t_c = (1/c) \quad [(R^2 + 4Yd)^{1/2} - R] \tag{1}$$

$$t_c = (1/c) \quad [(H^2 + (Y+d)^2)^{1/2} - (H^2 + (Y-d)^2)^{1/2}] \tag{2}$$

where t_c = surface cutoff time (ms)

c = sound speed at depth d (m/ms)

R = slant range between charge and gage (m)

Y = charge depth (m)

d = gage depth (m)

H = horizontal distance between charge and gage (m)

A value of c can be determined from the following equation:

$$c' = 1449.1 + 4.572(T-273.16) - .04453(T-273.16)^2 + 1.398(S-35) + .017d \quad \text{(Reference 7-1)} \tag{3}$$

$$c = c'/1000$$

where c' = sound speed (m/s)

c = sound speed (m/ms)

T = temperature in °K

S = salinity(ppt-parts per thousand)

d = depth (m)

The validity of Equation 3 is within less than 0.5% over the following range:

Temperature:	0 - 30°C
Salinity:	29 - 43 ppt
Depth:	0 - 10000 m

In the absence of temperature and salinity data, a value of between 1.44 and 1.54 m/ms can be chosen for the sound speed in water.

In cases where t_c is less than the integration times used to determine impulse and energy flux density, the measured values will be less than those predicted by the similitude equations for an underwater shock wave integrated to the usual limit of 5θ.

7-1 "Equation for the Speed of Sound in Water," Wilson W. D., Journal of the Acoustical Society of America, Volume 32, No. 10 October 1960.

CAVEAT: Equations (1) and (2) assume straight line propagation -- that is, no refraction.

PROBLEM EXAMPLE:

What is the surface cutoff time at a gage located at a depth of 60 meters, when a charge is at a depth of 30 meters, and the slant range between the charge and gage is 30 meters? The salinity is 35 ppt, and the water temperature is 15°C.

SOLUTION:

(1) $d = 60$ m

$Y = 30$ m

$R = 30$ m

$S = 35$ ppt

$T = 15°C = 288.16°K$

(2) $c' = 1449.1 + 4.572(15) - .04453(15)^2 + 1.398(35-35) + .017(60)$

$c' = 1508.17$ m/sec

(3) $c = 1.508$ m/ms

(4) $t_c = (1/c) \left[(R^2 + 4Yd)^{1/2} - R\right]$

$t_c = (1/1.508) \left[((30)^2 + 4(30)(60))^{1/2} - 30\right]$

$t_c = 39.79$ ms

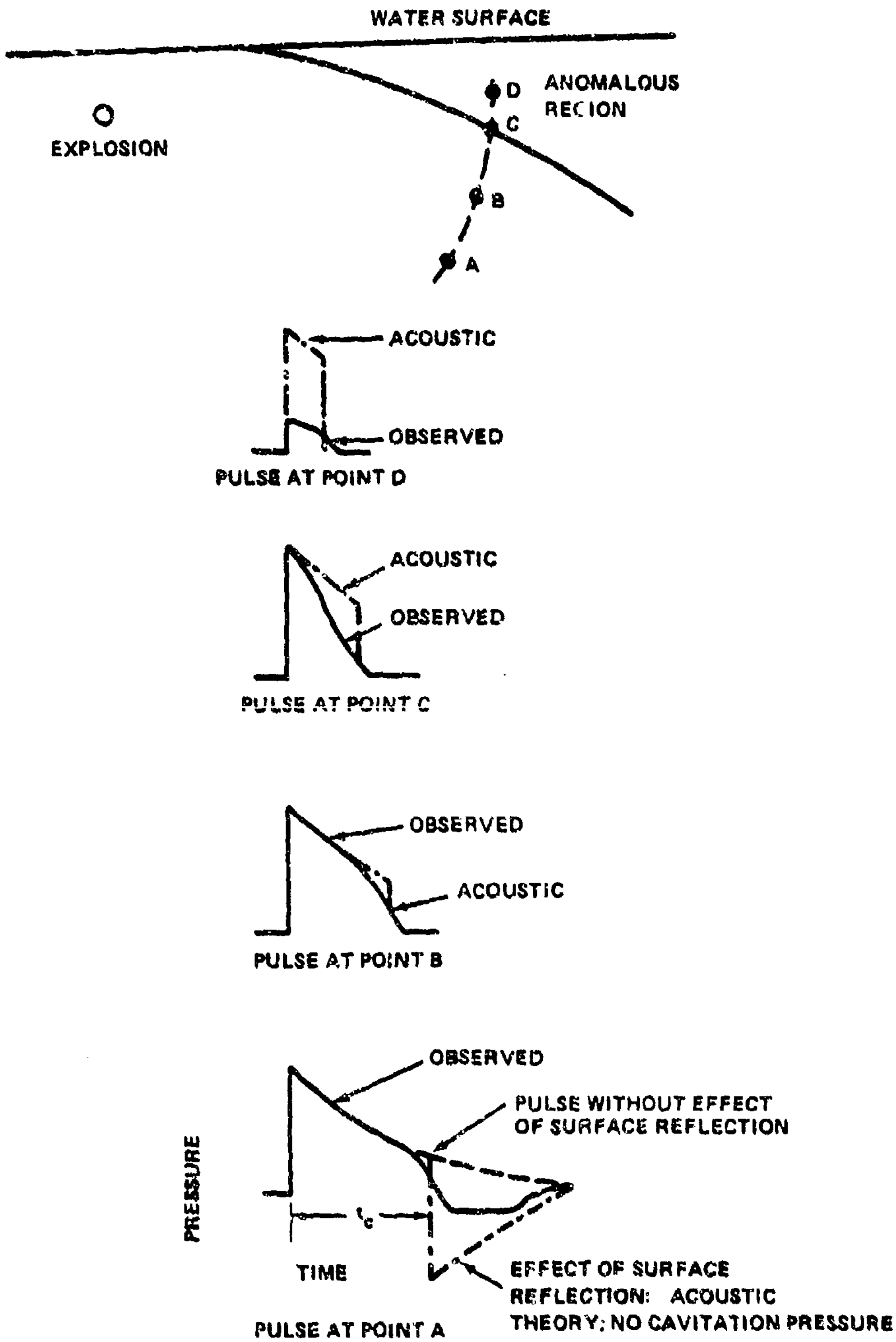


FIG. 7 TYPICAL PRESSURE PULSES AFFECTED BY SURFACE REFLECTION

CHAPTER 8. SHOCK WAVE ENERGY FROM CHARGES DETONATED ON THE BOTTOM*

Figure 8 and Table 8 present reduced shock wave energy vs. reduced distance for data derived from measurements using spherical HBX-1 charges weighing between 113 and 545 kilograms detonated on the bottom, with pressure gages located on or near the bottom. The water depth was 14 meters or greater. Two bottom conditions were included. These were "hard" -- of sand and oyster shell, and "soft" -- of mud several meters thick. The information is based on data which showed considerable scatter, especially at the smaller reduced distances.

*This information is from unpublished data of G. M. Davidson.

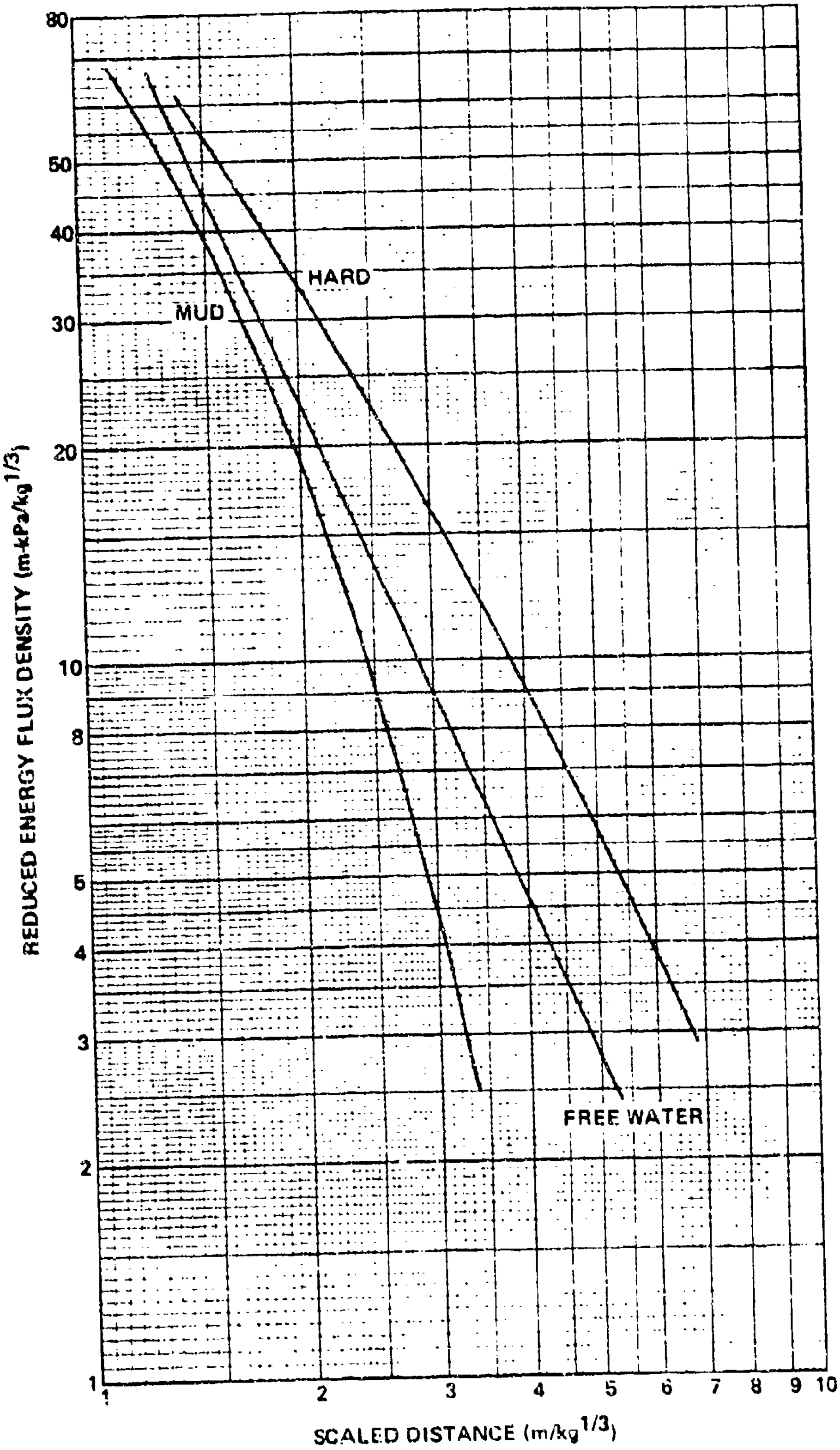


FIG. 8 REDUCED ENERGY AT THE BOTTOM VERSUS REDUCED DISTANCE FOR SPHERICAL HBX-1 CHARGES ON MUD AND HARD BOTTOM

TABLE 8 REDUCED ENERGY FLUX DENSITY VS. REDUCED DISTANCE FOR SPHERICAL HBX-1 CHARGES ON MUD AND HARD BOTTOM

SCALED DISTANCE ($m/kg^{1/3}$)	REDUCED ENERGY FLUX DENSITY ($m-kPa/kg^{1/3}$)	
	MUD	HARD
1.25	55.5	–
1.50	39.5	54.0
1.75	27.7	42.3
2.00	19.5	34.0
2.25	13.5	27.7
2.50	9.4	23.0
2.75	6.6	19.3
3.00	4.55	16.3
3.50	–	12.0
4.00	–	9.2
4.50	–	7.2
5.00	–	5.8
5.50	–	4.7
6.00	–	3.9

CHAPTER 9. THE UNDERWATER PEAK PRESSURE PRODUCED AT SHALLOW DEPTHS BY A SPHERICAL TNT CHARGE DETONATED AT THE WATER SURFACE

Near the surface of the water, the positive pressure pulse from an underwater explosion is affected by the presence of the surface. The maximum pressure in this region of so-called "anomalous surface cutoff" is considerably less than in free water. (For a discussion of surface cutoff, see Chapter 7).

This chapter presents the peak pressures to be expected at relatively shallow depths from a spherical TNT charge detonated with its center at the water surface.

CAVEAT: These curves are based on very limited experimental data and must be considered as approximations only. Their accuracy is no better than ± 15% in peak pressure. It is also assumed that the charge is over deep water.

The following symbols are used in this chapter:

- W Charge Weight in kilograms
- ρ TNT charge density (1600 kg/m^3)
- a Charge radius in meters
- R Distance to point of interest in meters
- d Gage depth in meters
- $\bar{R}$ Distance expressed in charge radii
- $\bar{d}$ Gage depth expressed in charge radii

PROBLEM EXAMPLE:

Determine the peak pressure at a point 2 meters deep and 30 meters away from a 343 kg charge of TNT detonated at the water surface.

SOLUTION I:

(1) $a = \left(\frac{3W}{4\pi\rho}\right)^{1/3}$

(2) $a = ((3 \times 343)/(4 \times 3.1416 \times 1600))^{1/3} = .371$ meters

(3) $\bar{R} = R/a = 30/.371 = 80.9$

(4) $\bar{d} = d/a = 2/.371 = 5.39$

(5) Enter Figure 10 with these values of $\bar{d}$ and $\bar{R}$ and read a pressure of 3.5 MPa

(6) As an alternative, with these values of $\bar{d}$ and $\bar{R}$, enter Table 10, and with suitable interpolation obtain a pressure of 3.54 MPa.

SOLUTION II:

Use of the nomograph attached to Figure 10:

1. With a straight edge, connect the weight and depth values on the horizontal scales (I and II) to find the depth in charge radii (5.3 on scale III). Draw a vertical line at this position.
2. With a straight edge, connect the weight and radial distance values on the vertical scales (IV and V) to find the radial distance in charge radii (80 on scale VI).
3. From scale VI, draw a line parallel to the nearest connecting line to the edge of the graph (Point A).
4. Starting at Point A, follow the curves down to the intersection (Point B) with previously determined vertical line for depth.
5. From Point B, follow a horizontal line to the pressure scale (VII) at the left of the graph and read P_m = 3.5 MPa.

The information in this chapter is from:

"On the Oblique Reflection of Underwater Shockwaves From a Free Surface. IV. Charges at the Surface," Christian, E. A., and Rosenbaum, J. H., NAVORD Report 3680, April 1954.

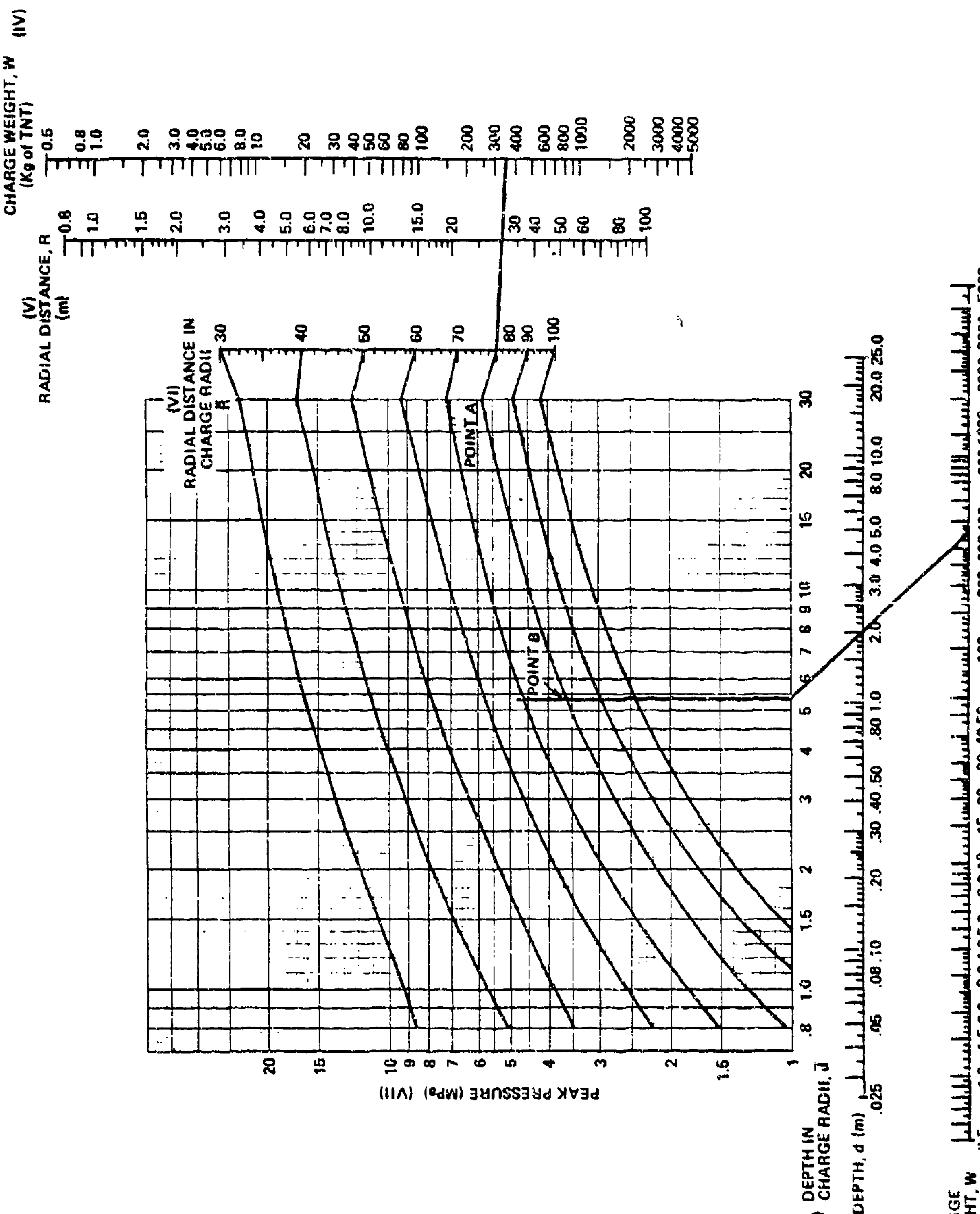


FIG. 9 PEAK UNDERWATER PRESSURES PRODUCED BY A SPHERICAL TNT CHARGE DETONATED AT THE WATER SURFACE

TABLE 9 PEAK UNDERWATER PRESSURES PRODUCED BY A SPHERICAL TNT CHARGE DETONATED AT THE WATER SURFACE

GAGE DEPTH IN CHARGE RADII	PEAK UNDERWATER PRESSURES (MPa)							
	RADIAL DISTANCE IN CHARGE RADII							
	100	90	80	70	60	50	40	30
0.8	–	–	1.07	1.52	2.20	3.46	5.04	8.53
0.9	0.69	0.90	1.17	1.67	2.41	3.71	5.31	9.03
1.0	0.74	0.98	1.29	1.82	2.60	3.91	5.72	9.30
1.5	1.09	1.37	1.77	2.43	3.30	4.72	6.96	10.85
2.0	1.37	1.71	2.15	2.92	3.85	5.32	7.78	11.90
2.5	1.60	1.96	2.50	3.32	4.29	5.89	8.45	12.81
3.0	1.79	2.21	2.76	3.67	4.63	6.31	9.10	13.54
3.5	1.96	2.40	2.97	3.91	4.90	6.70	9.53	14.18
4.0	2.11	2.59	3.20	4.14	5.18	7.09	9.98	14.85
5.0	2.36	2.89	3.47	4.50	5.67	7.65	10.75	15.84
6.0	2.57	3.14	3.78	4.76	6.00	8.22	11.36	16.60
7.0	2.76	3.29	4.00	5.05	6.32	8.60	11.90	17.37
8.0	2.89	3.45	4.[illegible]4	5.23	6.58	8.94	12.34	17.89
9.0	3.03	3.64	4.38	5.42	6.83	9.32	12.69	18.55
10.0	3.14	3.74	4.48	5.57	7.00	9.53	13.05	18.89
15.0	3.51	4.19	4.98	6.22	7.85	10.55	14.58	20.72
20.0	3.78	4.51	5.37	6.65	8.40	11.25	15.41	21.90
25.0	4.00	4.72	5.67	6.89	8.94	11.68	16.17	22.89
30.0	4.14	4.90	5.89	7.22	9.27	12.12	16.60	23.59

CHAPTER 10. BUBBLE PARAMETERS FOR VARIOUS HIGH EXPLOSIVES

The bubble period and bubble radius coefficients of an underwater explosion bubble in free water are given by the following equations:

$$K = T \frac{Z^{5/6}}{W^{1/3}} \qquad (1)$$

$$J = A_{max} \frac{Z^{1/3}}{W^{1/3}} \qquad (2)$$

where:

K = Bubble period coefficient ($s\text{-}m^{5/6}/kg^{1/3}$)

T = First bubble period (s)

Z = Hydrostatic pressure (charge depth (H) in meters + atmospheric head (H_o), also in meters -- approximately equals H + 10)

W = Charge weight (kg)

J = Bubble radius coefficient ($m^{4/3}/kg^{1/3}$)

A_{max} = Maximum bubble radius (m)

The Relative Bubble Energy (RBE) and the Relative Potential Bubble Energy (RPBE) have been previously defined in Chapter 1. Table 10 gives values of J, K, RBE, and RPBE for various explosives.

TNT is used in this chapter as the standard explosive for RBE and RPBE.

Equation (1) above, which relates K and T applies only to free water explosions, i.e., to depths and charge weights such that the bubble is not closer than about 10 bubble radii to either the surface or the bottom.

For cases where either the surface, the bottom, or both begin to influence the bubble, a correction equation relating K and T should be used.

One such equation is:

$$\frac{0.651\ \phi(y) W^{1/3}}{D Z^{1/3}} K^2 - K + \frac{T Z^{5/6}}{W^{1/3}} = 0 \qquad (3)$$

where:

H = Charge depth (m)

D = Total water depth (m)

$y = H/D$

$\phi(y)$ = function related to the bottom characteristics; $\phi(y)$ vs. y is presented in Figure 10

PROBLEM EXAMPLE:

An explosion bubble is found to have a period of 0.178 seconds for its first oscillation and a maximum radius of 3.65 meters. If the bubble is produced by the detonation of 100 kilograms of explosive at a depth of 150 meters in water of total depth 300 meters what are the J and K of the explosive? What is its RBE and RPBE relative to pentolite?:

SOLUTION:

(1) $W = 100$ kg, $W^{1/3} = 4.642$ kg$^{1/3}$

(2) $Z = H + 10 = 150 + 10 = 160$ meters

$Z^{1/3} = 5.429$ m$^{1/3}$; $Z^{5/6} = 68.670$ m$^{5/6}$

(3) $y = H/D = 150/300 = 0.5$

(4) From Equation (2):

$$J = A_{max} \frac{Z^{1/3}}{W^{1/3}}$$

$$J = (3.65)(5.429)/(4.642)$$

$$J = 4.27 \text{ m}^{4/3}/\text{kg}^{1/3}$$

(5) From Equation (1):

$$K = T \frac{Z^{5/6}}{W^{1/3}}$$

$$K = (0.178)(68.670)/(4.642)$$

$$K = 2.63 \text{ s-m}^{5/6}/\text{kg}^{1/3}$$

(6) Note that the expression derived for K in step (5) is the assumed free water value; to check the influence of the bottom and the surface, use Equation (3):

$$\frac{0.651\ \phi(y)\ W^{1/3}}{DZ^{1/3}} K^2 - K + \frac{T\ Z^{5/6}}{W^{1/3}} = 0$$

(7) From Figure 11, $\phi(y) = 0.83$ for $y = 0.5$

(8) $$\frac{(0.651)(0.83)(4.642)}{(300)(5.429)} K^2 - K + \frac{(0.178)(68.7)}{(4.642)} = 0$$

(9) $(1.54 \times 10^{-3}) K^2 - K + 2.63 = 0$

(10) Recognize this as a quadratic in K and solve:

$$K = \frac{1 \pm (1 - (4)(1.54 \times 10^{-3})(2.63))^{\frac{1}{2}}}{(2)(1.54 \times 10^{-3})}$$

(11) Choosing the negative sign,

$K = 2.65 \text{ s-m}^{5/6}/\text{kg}^{1/3}$

(12) From Table 11, K = 2.11 and J = 3.52 for pentolite

(13)

$$(RBE)_{pent} = \left(\frac{K_{experimental}}{K_{reference}}\right)^3$$

$$(RBE)_{pent} = \left(\frac{2.65}{2.11}\right)^3$$

$$(RBE)_{pent} = 1.98$$

(14)

$$(RPBE)_{pent} = \left(\frac{J_{experimental}}{J_{reference}}\right)^3$$

$$(RPBE)_{pent} = \left(\frac{4.27}{3.52}\right)^3$$

$$(RPBE)_{pent} = 1.79$$

The information in this chapter is from:

"Comparison of the Underwater Power of Explosives in Small Charges: 1. Miscellaneous Compositions," Niffenegger, C. R., NAVORD Report 2922, 1 July 1953.

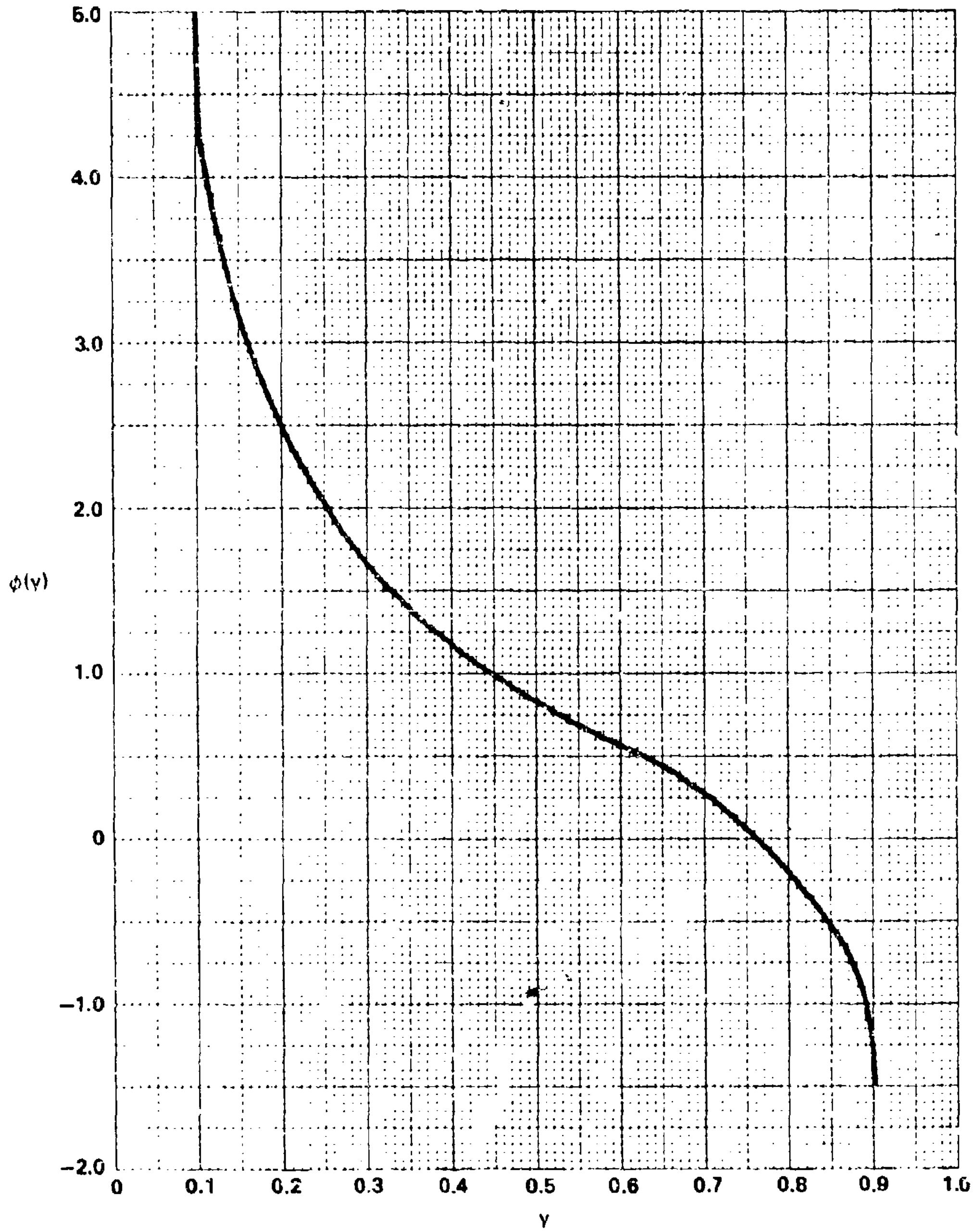


FIG. 10 BUBBLE PERIOD CONSTANT CORRECTION FACTORS

TABLE 10 BUBBLE PARAMETERS FOR VARIOUS HIGH EXPLOSIVES

EXPLOSIVE	J	K	$(RBE)_{TNT}$	$(RPBE)_{TNT}$
TNT	3.50	2.11	1.00	1.00
PENTOLITE	3.52	2.11	1.00	1.02
HBX-1	3.95	2.41	1.48	1.44
HBX-3	4.27	2.63	1.93	1.82
H-6	4.09	2.52	1.69	1.59

CHAPTER 11. FIRST PERIOD AND MAXIMUM RADIUS OF AN UNDERWATER GAS BUBBLE (TNT)

The nomogram presented in this chapter yields values of maximum radius and period of the first oscillation of the bubble of burnt gases formed by a TNT charge detonated underwater. The scales correspond to the following equations:

$$T = K \frac{W^{1/3}}{(H+H_o)^{5/6}} \tag{1}$$

$$A_{max} = J \frac{W^{1/3}}{(H+H_o)^{1/3}} \tag{2}$$

Where the symbols have the following definitions:

A_{max}	Maximum bubble radius (meters)
T	Period of oscillation (seconds)
W	Charge weight (kilograms)
H	Depth of charge (meters)
H_o	Atmospheric Head = 10 meters
K, J	Bubble coefficients dependent upon explosive

For TNT, $K = 2.11\ s\text{-}m^{5/6}/kg^{1/3}$ and $J = 3.50\ m^{4/3}/kg^{1/3}$. For explosives other than TNT, use the bubble parameters presented in Chapter 10.

CAVEAT: The above equation for T applies only to depths and weights such that the bubble is small relative to the total water depth, and is not closer than about 10 bubble radii to either the surface or the bottom. For other configurations, corrections, which amount to 15% at 2 bubble radii, must be applied.

PROBLEM EXAMPLE:

What is the maximum radius and period of the gas bubble produced by the detonation of 100 kg of TNT at a depth of 500 meters?

SOLUTION I:

(1) Use the Nomograph -- Figure 12.

(a) Connect 100 on the W scale with 500 on the D scale.

(b) Read a period T of 0.054 seconds and a maximum radius of 2.1 meters.

SOLUTION II:

(1) Substitute directly into Equations (1) and (2):

$$T = \frac{2.11\ (100)^{1/3}}{(500 + 10)^{5/6}}$$

$$T = (2.11 \times 4.64)/180.43$$

$$T = .054 \text{ seconds}$$

$$A_{max} = \frac{3.50\ (100)^{1/3}}{(500 + 10)^{1/3}}$$

$$A_{max} = 3.50 \times (100/510)^{1/3}$$

$$A_{max} = 2.033 \text{ meters}$$

The information in this chapter is from:

UNDERWATER EXPLOSIONS, Cole, R. H., Dover Publications, 1965.

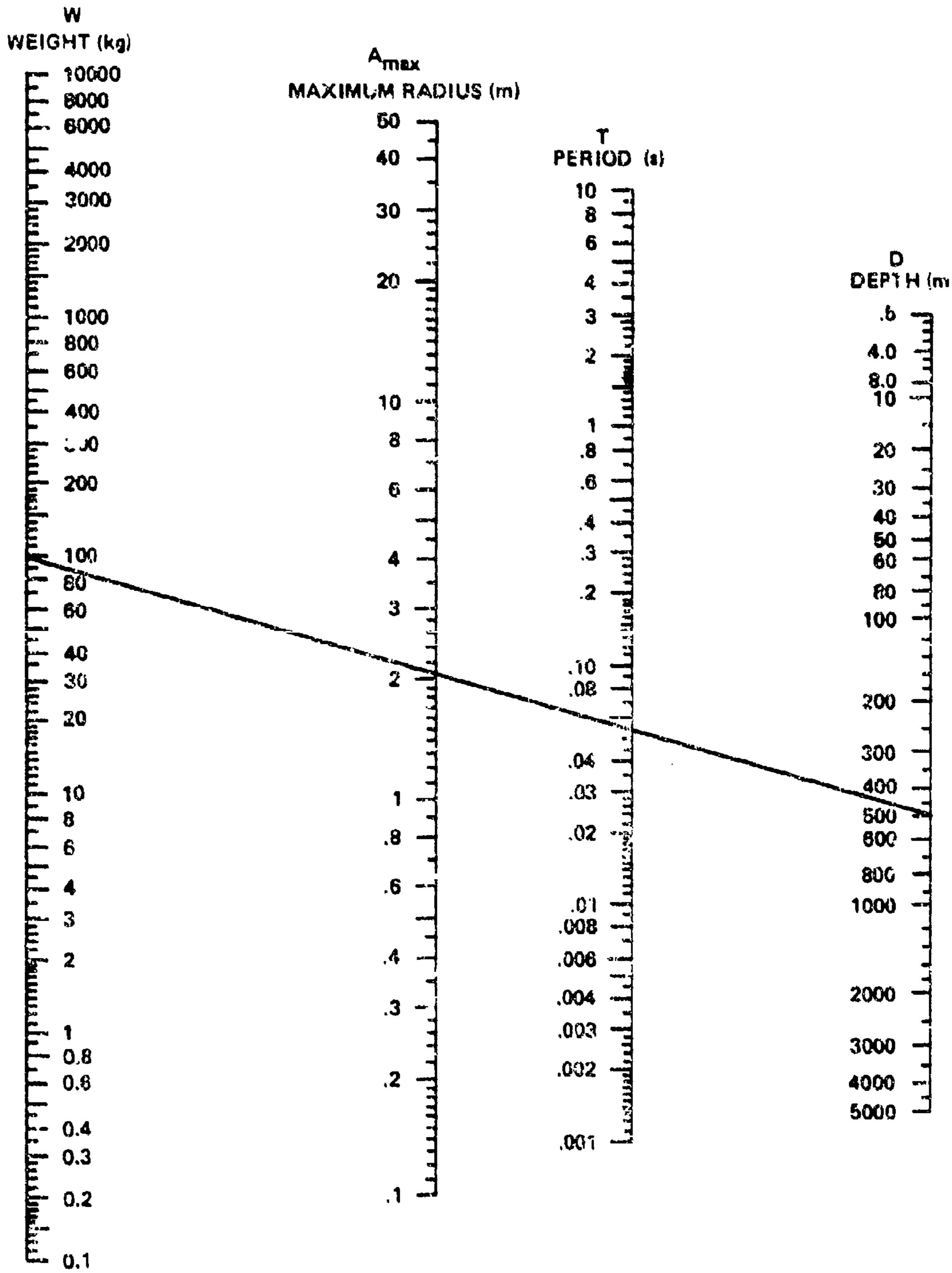


FIG. 11 FIRST PERIOD AND MAXIMUM RADIUS OF AN UNDERWATER GAS BUBBLE (TNT)

CHAPTER 12. NUMBER OF BUBBLE OSCILLATIONS BEFORE REACHING SURFACE FOR A MIGRATING TNT BUBBLE

This chapter can be used for predicting the phase of an underwater explosion bubble when it reaches the surface, for an explosion in which the bottom has no influence on migration.

One oscillation refers to the first minimum bubble radius; two oscillations, to the second minimum; 0.5 oscillations, to the first maximum, etc.

The information presented in this chapter is valid for TNT charges weighing between 140 and 900 kg. For explosives other than TNT, first multiply the charge weight by their $(RBE)_{TNT}$ (See Table 10).

PROBLEM EXAMPLE 1:

For a 729 kg charge of TNT detonated at a depth of 36 meters, how many bubble oscillations will occur before the bubble reaches the surface?

SOLUTION:

(1) $W = 729$ kg, $W^{1/3} = 9.00\ kg^{1/3}$

(2) $d = 36$ m, $d/W^{1/3} = 36/9 = 4.00\ m/kg^{1/3}$

(3) Enter either Figure 12 or Table 12 with this value of reduced charge depth and read N = 3.07 oscillations. Thus the third bubble minimum has just been passed.

PROBLEM EXAMPLE 2:

For a 500 kg charge of H-6 detonated at a depth of 25 meters, how many bubble oscillations will occur before the bubble reaches the surface?

The information in this chapter is from:

"The Hydrodynamic Background of the Radiological Effects of Underwater Nuclear Explosions," Snay H. G., NAVWEPS 7323, September 1960.

SOLUTION:

(1) $W = 500$ kg

(2) From Table 10, the $(RBE)_{TNT}$ for H-6 is 1.69

(3) $W_{TNT} = 500 \times 1.69 = 845$ kg, $W^{1/3} = 9.45$ kg$^{1/3}$

(4) $d = 25$ m, $d/W^{1/3} = 25/9.45 = 2.64$ m/kg$^{1/3}$

(5) Enter Figure 12 with this value of reduced distance and read N = 1.95 oscillations.

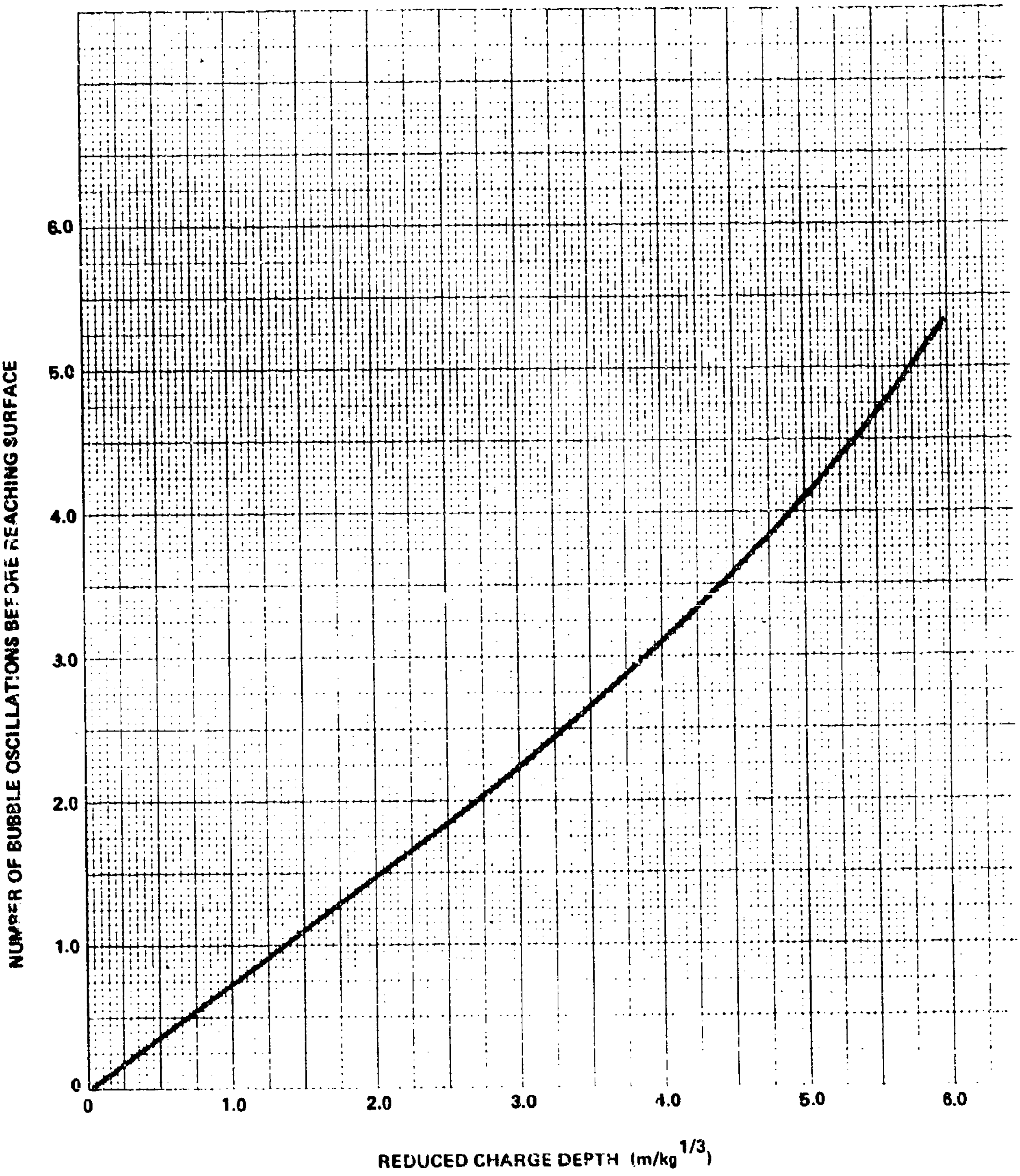


FIG. 12 NUMBER OF BUBBLE OSCILLATIONS BEFORE BUBBLE REACHES SURFACE (FOR A TNT BUBBLE)

TABLE 12 NUMBER OF BUBBLE OSCILLATIONS BEFORE BUBBLE REACHES SURFACE (FOR A TNT BUBBLE)

REDUCED CHARGE DEPTH $d/w^{1/3}$ ($m/kg^{1/3}$)	NUMBER OF BUBBLE OSCILLATIONS BEFORE REACHING SURFACE
0	0
0.5	0.37
1.0	0.72
1.5	1.08
2.0	1.45
2.5	1.83
3.0	2.22
3.5	2.65
4.0	3.07
4.5	3.55
5.0	4.07
5.5	4.68
6.0	5.37

CHAPTER 13. COLUMN AND JET FORMATION BY A SHALLOW UNDERWATER EXPLOSION

The equations and table presented in this chapter can be used for predicting the maximum column and smoke plume diameters and the maximum height of the jet formed by a relatively shallow underwater explosion when the charge is placed on the bottom. However, there is no positive evidence that jet heights are different when shallow explosions take place in deep water.

Shown in Figure 13 are the definitions of the terms S_{max}, D_{max}, and H_{max}. W is the charge weight in kilograms, and Y is the charge depth in meters.

(1) $H_{max}/W^{1/3} = 32.4\ (Y/W^{1/4})^{.1}$ $\quad .0037 < Y/W^{1/4} < .74$

(2) $H_{max}/W^{1/3} = 21.7\ (Y/W^{1/4})^{-1.24}$ $\quad .74 < Y/W^{1/4} < 1.56$

(3) $D_{max}/W^{1/3} = 3.71\ (Y/W^{1/3})^{.166}$ $\quad .08 < Y/W^{1/3} < .88$

(4) $S_{max}/W^{1/3} = 9.00$ $\quad .04 < Y/W^{1/3} < .24$

where:

$H_{max}/W^{1/3}$ = Scaled Maximum Jet Height ($m/kg^{1/3}$)

$D_{max}/W^{1/3}$ = Scaled Maximum Column Diameter ($m/kg^{1/3}$)

$S_{max}/W^{1/3}$ = Scaled Maximum Smoke Crown Diameter ($m/kg^{1/3}$)

For explosives other than TNT, first multiply the charge weight by the $(RBE)_{TNT}$.

CAVEAT: For Safety Considerations, add 30% to D_{max} and 40% to H_{max}.

PROBLEM EXAMPLE:

If a 1000 kg TNT charge is detonated at a depth of 2 meters, what is the maximum height of the jet, the maximum column diameter, and the maximum smoke crown diameter?

SOLUTION:

(1) W = 1000 kg, $W^{1/4}$ = 5.62, $W^{1/3}$ = 10.

(2) $Y = 2$, $Y/W^{1/4} = 2/5.62 = .36$, $Y/W^{1/3} = 2/10 = .20$

(3) Use Equation (1) for $H_{max}/W^{1/3}$

$$H_{max}/W^{1/3} = 32.4\ (Y/W^{1/4})^{.1}$$

$$H_{max} = 10 \times 32.4\ (.36)^{.1}$$

$$H_{max} = 292.5 \text{ meters}$$

(4) Use Equation (3) for $D_{max}/W^{1/3}$

$$D_{max}/W^{1/3} = 3.71\ (Y/W^{1/3})^{.166}$$

$$D_{max} = 10 \times 3.71\ (.2)^{.166}$$

$$D_{max} = 28.4 \text{ meters}$$

(5) Use Equation (4) for $S_{max}/W^{1/3}$

$$S_{max}/W^{1/3} = 9.0$$

$$S_{max} = 10 \times 9.0$$

$$S_{max} = 90 \text{ meters}$$

An alternativ to using equations (1), (3), and (4) for the solution of this problem is to use Table 13. By entering this table with the appropriate values of scaled depth and performing several interpolations, the same results may be obtained.

The information in this chapter is from:

"The Scaling of Base Surge Phenomena of Shallow Underwater Explosions; interim Report No. 9," Milligan, M. L., and Young, G. A., NAVORD Report 2987, May 1954.

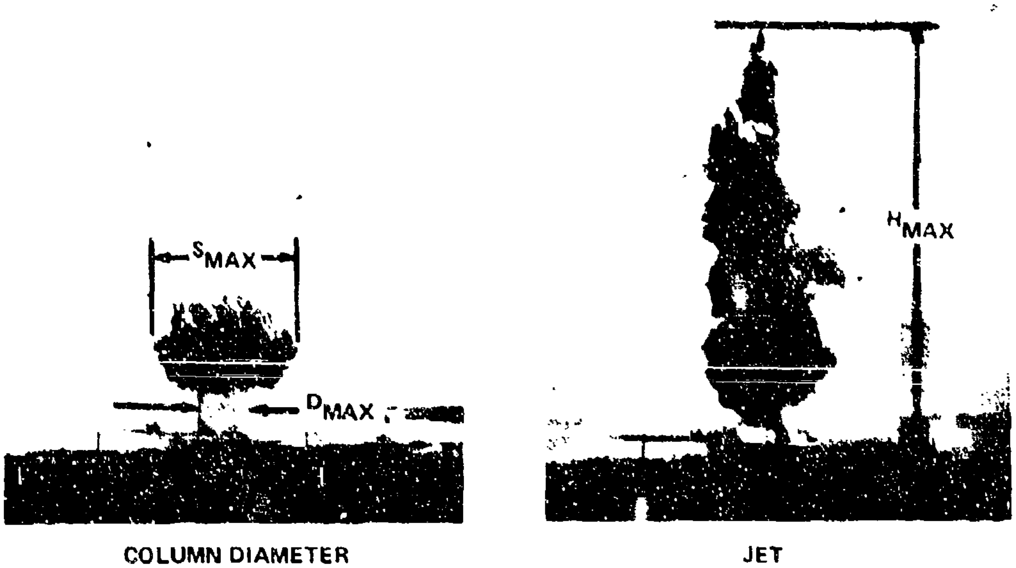


FIG. 13 COLUMN AND JET FORMATION BY A SHALLOW UNDERWATER EXPLOSION

TABLE 13 COLUMN AND JET PARAMETERS

SCALED DEPTH*	SCALED MAXIMUM JET HEIGHT, H_{max} $(m/kg^{1/3})$	SCALED MAXIMUM COLUMN DIAMETER, D_{max} $(m/kg^{1/3})$	SCALED MAXIMUM SMOKE CROWN DIAMETER $(m/kg^{1/3})$
.004	18.7		
.005	19.1		
.006	19.4		
.007	19.7		
.008	20.0		
.009	20.2		
.01	20.4		
.02	21.9		
.03	22.8		
.04	23.5		9.0
.05	24.0		9.0
.06	24.5		9.0
.07	24.8		9.0
.08	25.2	2.44	9.0
.09	25.5	2.48	9.0
.10	25.7	2.53	9.0
.20	27.6	2.84	9.0
.30	28.7	3.03	
.40	29.6	3.18	
.50	30.2	3.30	
.60	30.8	3.40	
.70	31.3	3.49	
.30	28.6	3.57	
.90	24.7		
1.00	21.7		
1.10	19.3		
1.20	17.3		
1.30	15.7		
1.40	14.3		
1.50	13.1		

*NOTE, THAT THE SCALED DEPTH IS EITHER $m/kg^{1/4}$ or $m/kg^{1/3}$, depending on whether one is calculating H_{max} or D_{max}.

CHAPTER 14. MAXIMUM HEIGHT AND RADIUS OF THE PLUMES FROM AN UNDERWATER TNT EXPLOSION *

This chapter presents information which can be used for predicting the size of the plumes formed by an underwater TNT explosion, either on or off the bottom.

Figure 14-1 shows a typical plume and defines both the maximum height and radius.

For explosives other than TNT, first multiply the charge weight by the $(RBE)_{TNT}$.

CAVEAT: The curves and tables presented in this chapter were developed for the establishment of safe distances. Actual plume demensions may be as much as 50% less in some cases.

PROBLEM EXAMPLE:

What is the maximum plume height and radius produced by the detonation of 500 kg of TNT at a depth of 30 meters.

SOLUTION:

(1) $W = 500$ kg, $W^{1/4} = 4.73$ kg$^{1/4}$, $W^{1/3} = 7.94$ kg$^{1/3}$

(2) $Y = 30$ meters

$Y/W^{1/4} = 30/4.73 = 6.34$ m/kg$^{1/4}$

(3) With this value of scaled charge depth, enter either Figure 14-1 or Table 14, and read (with suitable interpolation):

Scaled Radius = 7.75 m/kg$^{1/3}$

Scaled Height = 7.05 m/kg$^{1/3}$

(4) Radius = 7.75 X 7.94 = 61.5 meters

Height = 7.05 X 7.94 = 56.0 meters

*The information in this chapter is unclassified data from a classified reference.

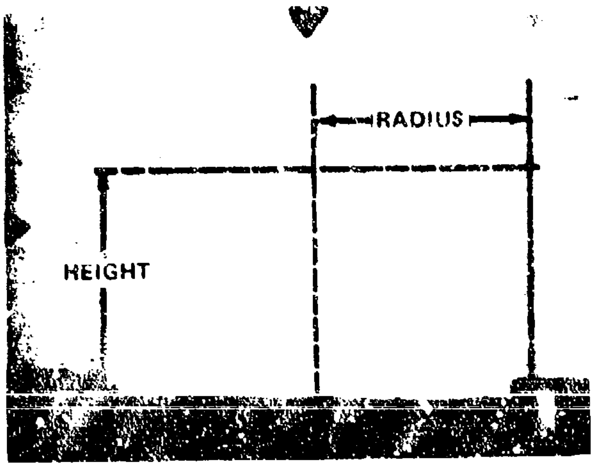


FIG. 14-1 PLUME DIMENSIONS

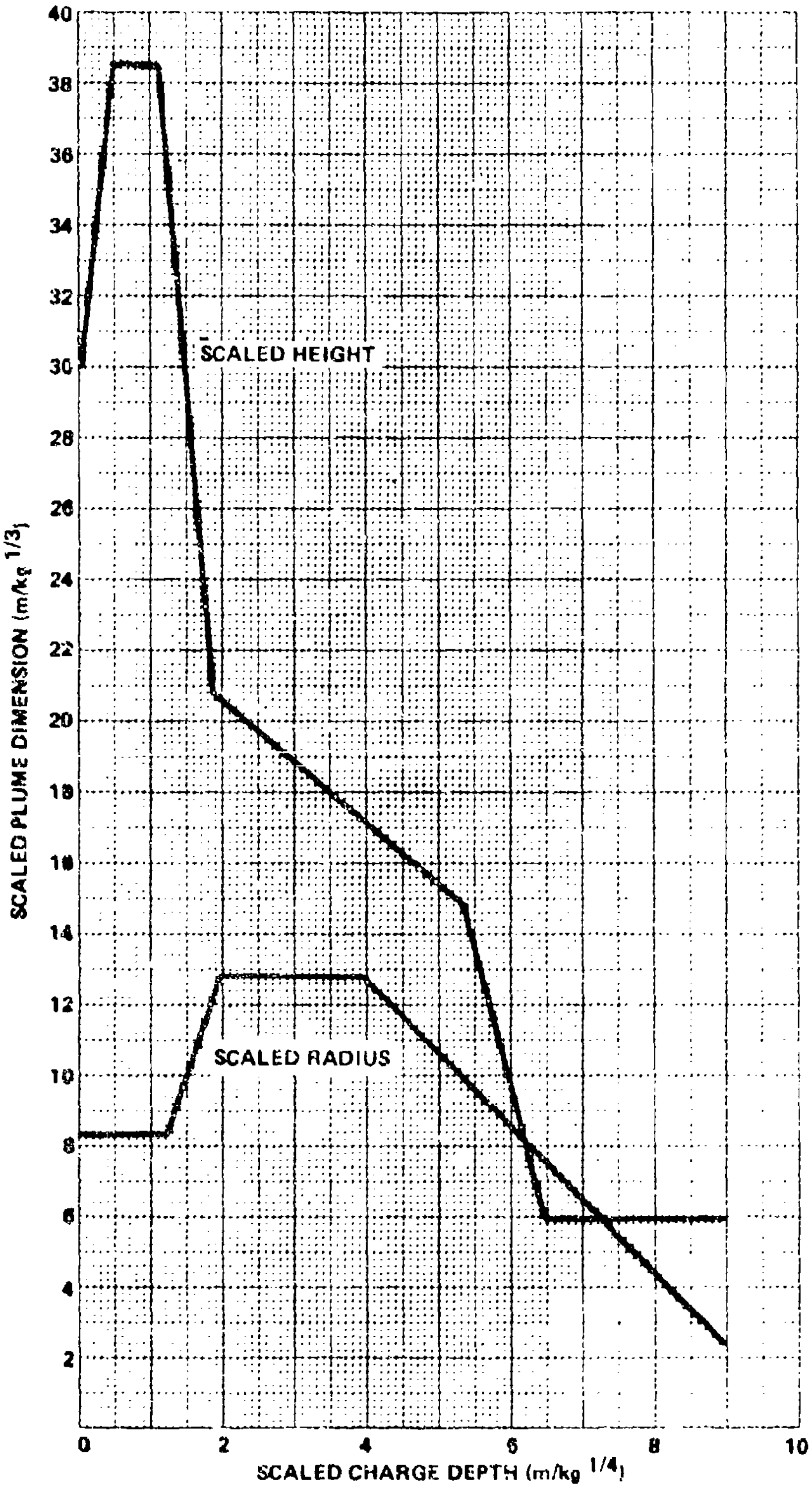


FIG. 14-2 MAXIMUM HEIGHT AND RADIUS OF THE PLUME FROM AN UNDERWATER TNT EXPLOSION

TABLE 14 MAXIMUM HEIGHT AND RADIUS OF THE PLUME FROM AN UNDERWATER TNT EXPLOSION

SCALED CHARGE DEPTH $(m/kg^{1/4})$	SCALED RADIUS $(m/kg^{1/3})$	SCALED HEIGHT $(m/kg^{1/3})$
0	8.3	29.7
0.5	8.3	38.6
1.0	8.3	38.6
1.5	10.0	29.0
2.0	12.8	20.6
2.5	12.8	19.7
3.0	12.8	18.9
3.5	12.8	18.0
4.0	12.8	17.1
4.5	11.6	16.2
5.0	10.6	15.4
5.5	9.5	13.6
6.0	8.5	9.5
6.5	7.4	5.9
7.0	6.4	5.9
7.5	5.4	5.9
8.0	4.3	5.9
8.5	3.3	5.9
9.0	2.3	5.9

CHAPTER 15. ENERGY FLUX SPECTRUM FOR EXPONENTIAL APPROXIMATIONS OF SHOCK WAVES

For an exponentially decaying pulse, the Fourier integral for the energy flux spectrum level is:

$$E(f) = \frac{2}{\rho_o c_o} \left[\frac{P^2\theta^2}{(1+\omega^2\theta^2)}\right] \qquad (1)$$

where P is the initial pressure of the wave, θ is the decay constant, $\rho_o c_o$ is the acoustic impedance, and $\omega = 2\pi f'$, where f' is the frequency in Hertz. For an explosion shockwave, P and θ can be determined from the similitude equations presented in Chapter 2. Let us choose the similitude equation for TNT, namely:

$$P = 52.4 \; (W^{1/3}/R)^{1.13} \qquad (2)$$

$$\theta = .000084 \; (W^{1/3}/R)^{-.23} \; W^{1/3} \qquad (3)$$

where the pressure, P, is in MPa, W is the charge weight in kg, R is the slant range in meters, and θ is the time constant in seconds.

Substituting Equations (2) and (3) into Equation (1) yields,

$$E(f) = \frac{24.669 \; R^{-1.80} \; W^{1.27}}{1+.279 \; [fW^{.26}R^{.23}]^2} \qquad (4)$$

where R and W are defined as above, f is the frequency in kHz, and E(f) is in Joules/m^2/Hz.

The Energy Level, E(dB) = 10 log $(E(f)/E_{ref})$. E_{ref} is the energy level of a 1μPa signal, namely, 1μJ/m^2/Hz. Thus,

$$E(dB) = 10 \log (E(f)) + 60 \quad (\text{re } 1 \; \mu Pa) \qquad (5)$$

CAVEAT: The exponential approximation neglects the slowly-decaying pressure observed in the tail of the shock wave. Therefore, Equation (4) gives energies too low at low frequencies. Equation (4) is valid within the frequency range of 0.5 to 10 kHz

PROBLEM EXAMPLE:

What is the Energy Flux Spectrum (E(f)) and the energy level (E(dB)) at a frequency of 2 kHz at a distance of 50 meters from a 2 kg TNT explosion.

SOLUTION:

(1)

$$E(f) = \frac{24.669\ R^{-1.80}\ W^{1.27}}{1 + .279\ \left[fW^{.26}R^{.23}\right]^2}$$

$$E(f) = \frac{24.669(50)^{-1.80}(2)^{1.27}}{1 + .279\ \left[(2)(2)^{.26}(50)^{.23}\right]^2}$$

$$E(f) = \frac{(24.669)(.0008747)(2.41)}{1 + .279\ \left[(2)(1.2)(2.46)\right]^2}$$

$$E(f) = \frac{.0520}{1 + .279(34.8572)}$$

$$E(f) = .0048\ \ J/m^2/Hz$$

(2)

$$E(dB) = 10 \log (E(f)) + 60$$

$$E(dB) = 36.8\ dB\ \ re\ \ 1\ \mu Pa$$

The information in this chapter is from:

"Scaling the Energy Spectra of Underwater Explosion Shockwaves," Christian, E. A., NOLTR 62-36, June 1963.

CHAPTER 16. SHOCK WAVE PEAK PRESSURE AND ENERGY FLUX DENSITY PRODUCED BY THE DETONATION OF LINE CHARGES

The curves presented in this chapter give free-water shock wave information for line charges detonated at one end. Information is presented for measurements taken in three directions: (1) off the detonator end, (2) off the end opposite the detonator, and, (3) along the perpendicular bisector of the charge.

The charges were all Mark 8 Demolition Charges, loaded with "flexed" TNT. Each unit was 7.62 meters long, 0.05 meters in diameter, and weighed 7.62 kilograms.

The information presented in Figures 16-1 and 16-2 have not been "scaled" (reduced), since there is some question as to the proper way to "scale" line charge information.

The infromation in this chapter is from:

"Shock-Wave Parameters Measured Off the Ends and Perpendicular Bisector of Line Charges 25 ft Long Containing 50 lb of Flexed TNT," Coles, J. S., Cole, R. H., Cross, P. C., Slifko, J. P., Niffenegger, C. R., Christian, E. A., and Rogers, M. A., NAVORD Report 102-46, 3 July 1947.

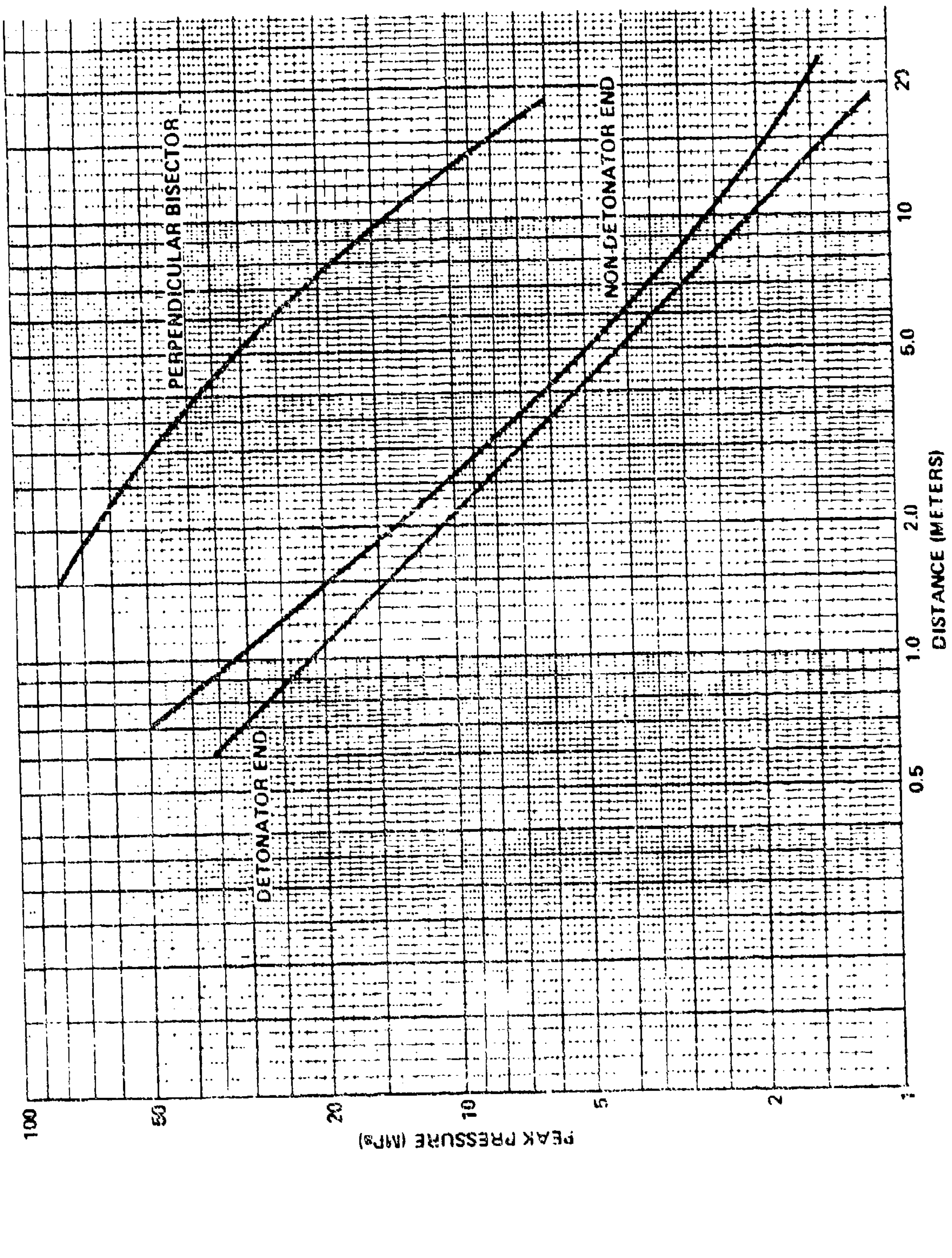


FIG. 16-1 PEAK PRESSURES PRODUCED BY LINE CHARGES

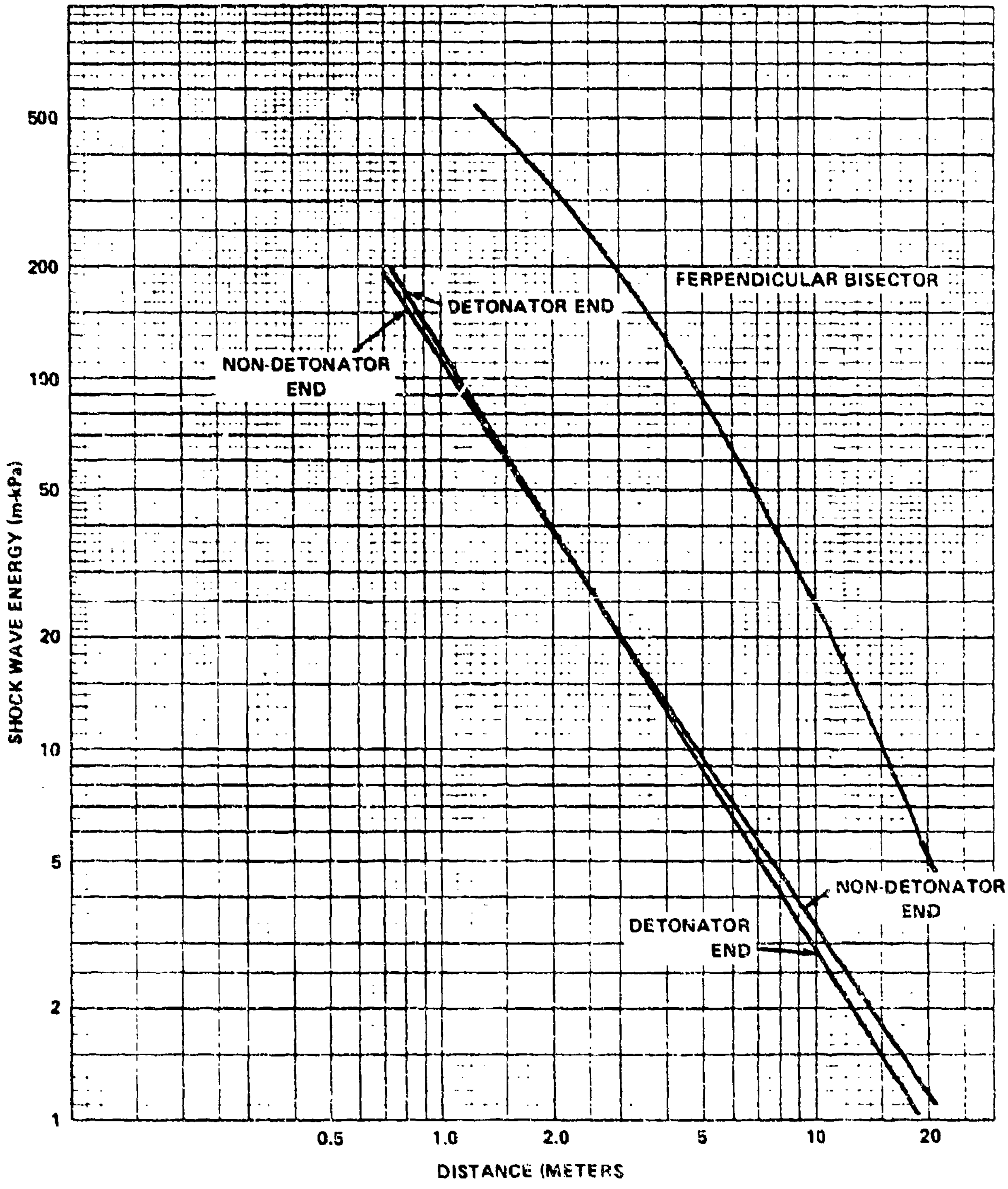


FIG. 16-2 SHOCK WAVE ENERGIES PRODUCED BY LINE CHARGES

CHAPTER 17. ESTIMATION OF SHOCK WAVE SPECTRAL ENERGIES FOR LINE CHARGES AT SHALLOW DEPTHS

To estimate the shock wave spectral energy per unit area for different conditions (i.e., charge length, charge weight, range, and explosive) the following method can be used:

$$E_2 = \frac{E_1}{\beta} \left[\frac{I_2}{I_1}\right]^2$$

where E_2 is the energy/unit area for the new condition in a frequency band ΔF_2 for the same emission angle measured for E_1. (ΔF_2 must be $1/\beta$ times one of the six octave bands for which data are plotted in Figure 17).

E_1 is the energy/unit area for the 3.05 meter, 0.9 kg EL506D charge at 24.4 meters range. E_1 is read from the appropriate curve (Figure 17) for a given emission angle in the $\beta(\Delta F_2)$ band.

$$\beta = \left[\frac{L_2}{L_1}\right] \left[\frac{c_1}{c_2}\right]$$

where L_2 and L_1 are the lengths of the new charge and the 3.05 m, 0.9 kg charge respectively. c_2 is the estimated sound velocity in the water for the new conditions ($c_1 = 1463$ m/s).

$$\left[\frac{I_2}{I_1}\right]^2 = k \left[\frac{W_2}{W_1}\right]^{4/3} \left[\frac{R_1}{R_2}\right]^2$$

k = 1.0 for EL506D explosive

k = 1.54 for PETN primacord

W_2 and R_2 are the charge weight and range for the new conditions; W_1 and R_1 are 0.9 kg and 24.4 m respectively.

CAVEATS: (1) The range must be equal to or greater than 8 times the charge length.
(2) The length-to-diameter ratio of the charge must be at least 50.

(3) The explosive (including detonators) must be evenly distributed along the length of the charge.
(4) The transmission of sound in the medium must be uniform.
(5) For a single-end-initiated charge, the angle, ϕ, at which the maximum energy occurs is a function of the detonation velocity of the explosive, v, and the velocity of sound in the water, c. $\phi \approx \sin^{-1}(c/v)$. For EL506D and PETN primacord, v can vary from about 6400 m/s to 7600 m/s; c varies from about 1400 m/s to 1550 m/s. Thus, ϕ varies from about 10 degrees to about 14 degrees.

PROBLEM EXAMPLE:

Desired Conditions:

Charge type: single-end initiated charge
Charge Composition: PETN
Charge Length: $L_2 = 6.1$ meters
Charge Weight: $W_2 = 2.27$ kg
$\Delta F_2 \approx 2$ to 4 kHz
Emission Angle: +55 degrees
Range: $R_2 = 91.4$ meters
Sound Velocity: $c_2 = 1524$ m/s

SOLUTION:

(1) $$\beta = \left[\frac{L_2}{L_1}\right]\left[\frac{c_1}{c_2}\right] = (6.1/30.5)(1463/1524)$$

$$\beta = 1.92$$

(2) $E_1 = 0.930\ \mathrm{J/m^2}$ (ΔF_1 is the 4 to 8 kHz filter band curve in Figure 17).

(3) $$\left[\frac{I_2}{I_1}\right]^2 = k\left[\frac{W_2}{W_1}\right]^{4/3}\left[\frac{R_1}{R_2}\right]^2$$

$$\left[\frac{I_2}{I_1}\right]^2 = 1.54\ (2.27/0.9)^{4/3}\ (24.4/91.4)^2$$

$$\left[\frac{I_2}{I_1}\right]^2 = 0.376$$

(4) $$E_2 = \left[\frac{E_1}{\beta}\right]\left[\frac{I_2}{I_1}\right]^2 \qquad E_2 = (0.930/1.92)(0.376)$$

$E_2 = 0.182\ \mathrm{J/m^2}$ for the 2.08 to 4.17 kHz band (i.e., $\Delta F_2 \approx 2$ to 4 kHz)

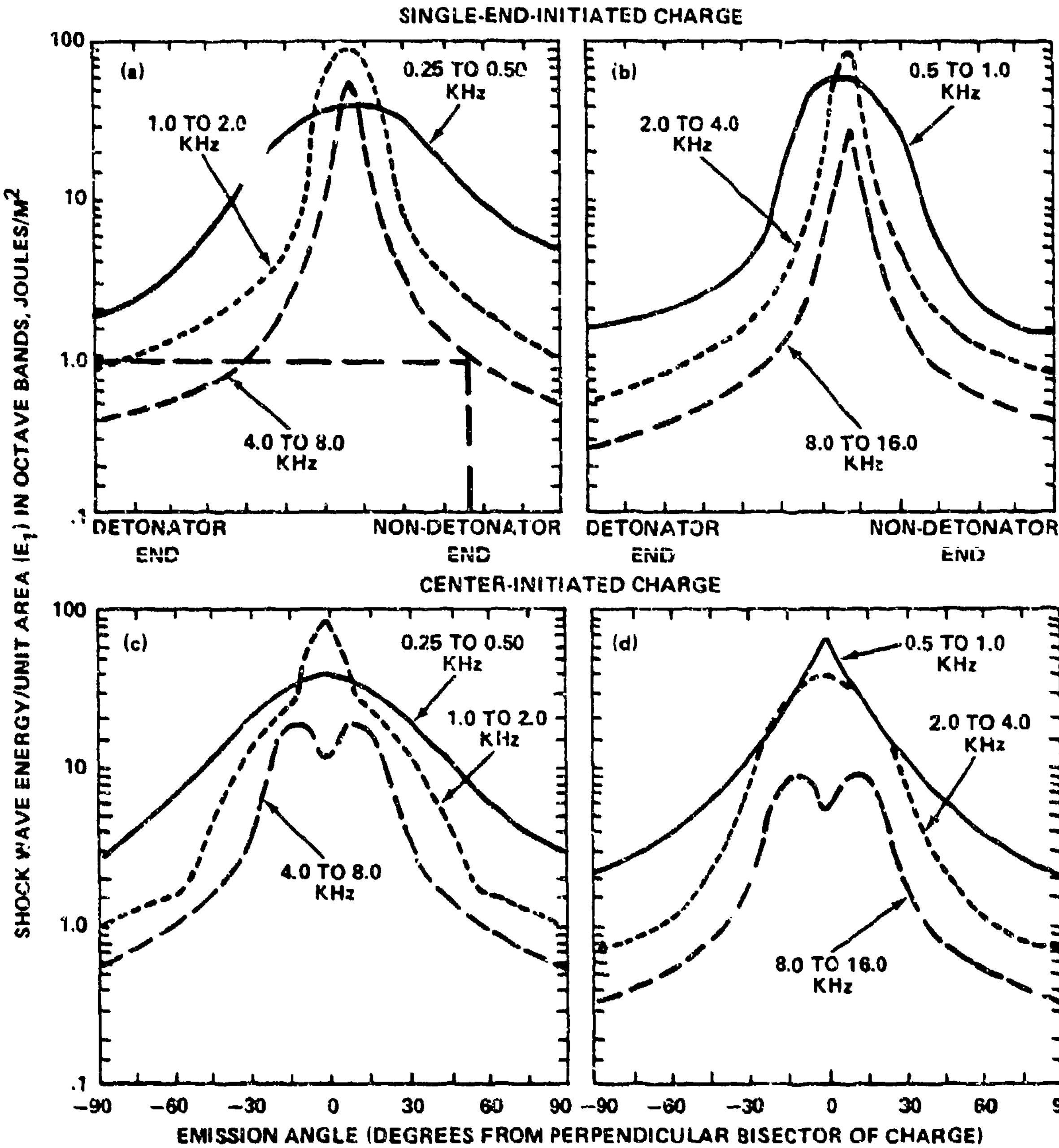


FIG. 17-1 SHOCK WAVE ENERGY/UNIT AREA IN OCTAVE BANDS FOR 3.05 METER LONG, 0.9kg EL 506D CHARGES AT A RANGE OF 24.4 METERS AT SHALLOW DEPTH

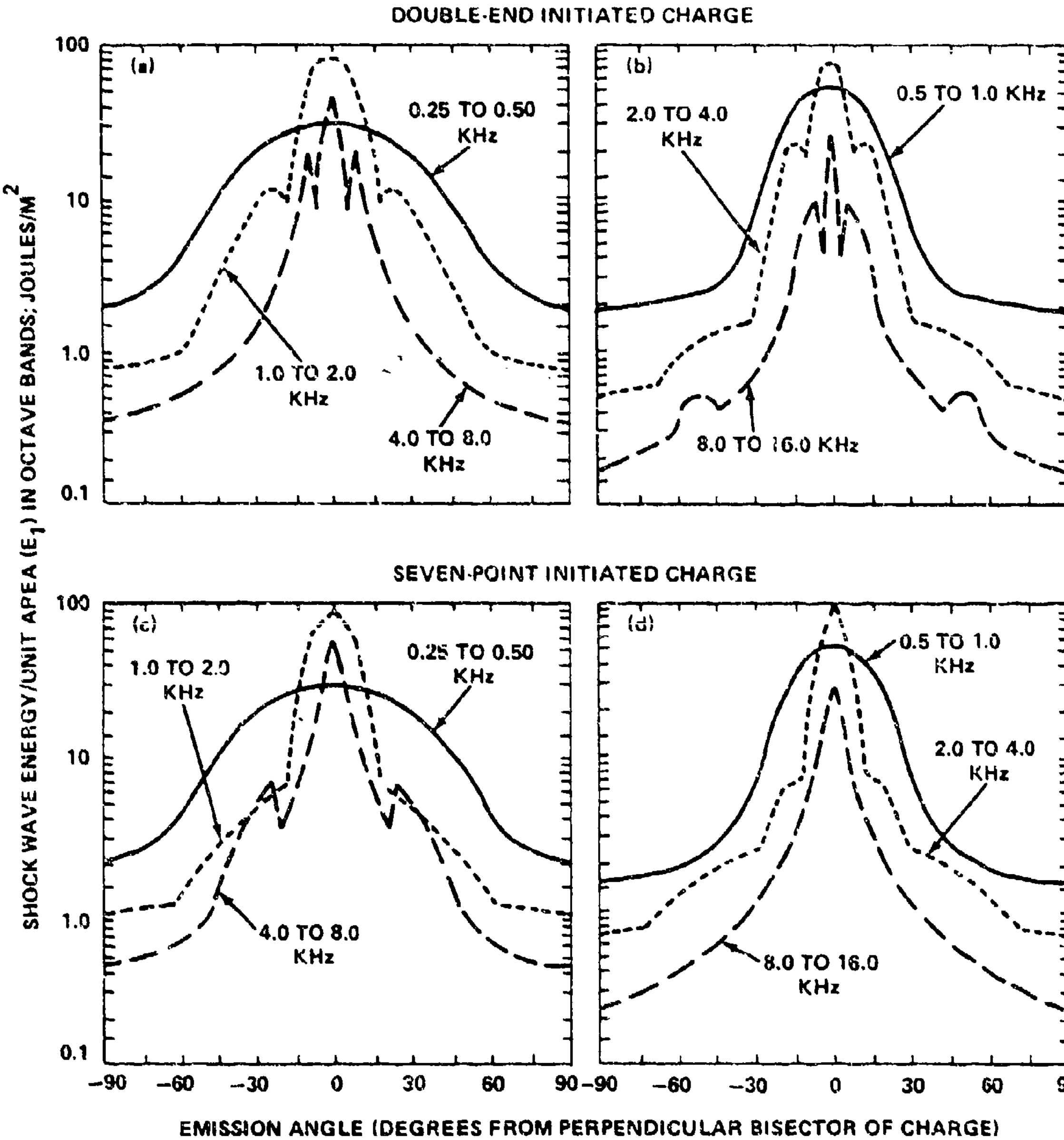


FIG. 17-2 SHOCK WAVE ENERGY/UNIT AREA IN OCTAVE BANDS FOR 3.05 METER LONG, 0.9 kg EL 506D CHARGES AT A RANGE OF 24.4 METERS AT SHALLOW DEPTH

CHAPTER 18. SOURCE LEVELS FOR DEEP UNDERWATER EXPLOSIONS

When an explosion is used as an acoustic source, a source level (SL) is needed for use in the sonar equations. Determination of such levels with high precision is quite difficult. The methods of this chapter can be used to obtain an approximate number. The source levels so obtained are good, at best, to ± 1 dB.

The information presented below may be used to calculate source energy levels for explosions at depths from 90 to 6700 meters. The information presented in Figure 18 and Table 18 are used in conjunction with the following equation for the fundamental frequency of the bubble pulse:

$$f_b = K^{-1} Z^{5/6} W^{-1/3} \tag{1}$$

where:

f_b = bubble pulse frequency (Hz)

K = bubble period coefficient ($s\text{-}m^{5/6}/kg^{1/3}$)

Z = hydrostatic pressure (meters of water) -- approximately equal to the charge depth in meters + 10

W = charge weight (kg)

R = slant range (m)

SL = source level = 10 log E (dB re $1\mu J/m^2/Hz$)

Values for K are presented in Chapter 10 for various explosives.

Both Figure 18 and Table 18 give reduced energy flux spectra as a function of reduced frequency. The data here are smoothed from octave band spectra. At frequencies greater than about 10 f_b, these numbers will differ little from narrower band spectra, i.e., 1/3-octave bands.

CAVEAT: Near the charge, where nonlinear effects predominate, the success of the method presented in this chapter will be variable -- for some combinations of charge weight, range, burst depth, and frequency, it is adequate -- for other combinations, it is not. It appears that the range at which an explosion sound field approaches a more or less steady state, and hence can be realistically described in terms of the usual sonar equation parameters, may be some thousands of meters distant from the source.

PROBLEM EXAMPLE:

Find the source level for a 20 kg pentolite charge at a 1200 meter depth of burst in an octave band centered at 500 Hz at a range of 2000 meters.

PROBLEM SOLUTION:

(1) From Table 10, the K for pentolite is 2.11 $s\text{-}m^{5/6}/kg^{1/3}$

(2) $f_b = K^{-1}\, Z^{5/6}\, W^{-1/3}$

(3) $f_b = (2.11)^{-1}(2000 + 10)^{5/6}(20)^{-1/3}$

$f_b = (565.8)/(2.11)(2.71)$

$f_b = 98.8$ Hz

(3) $f/f_b = 500/98.8 = 5.06$

(4) Enter either Table 18 or Figure 18 with this value of f/f_b and read:

$$10 \log E - (40/3)\log (2.20W) + 20 \log (R/91.44) = 47.9$$

(5) $SL = 10 \log E = 47.9 + (40/3)\log(2.20 \times 20) - 20\log(2000/91.44)$

(6) $SL = 47.9 + 21.9 - 26.8$

(7) $SL = 43$ dB re $1 \mu J/m^2/Hz$

The information in this chapter is from:

"Source Levels for Deep Underwater Explosions," Christian, E. A., Journal of the Acoustical Society of America, Vol. 42 No. 4, 905-907, October 1967.

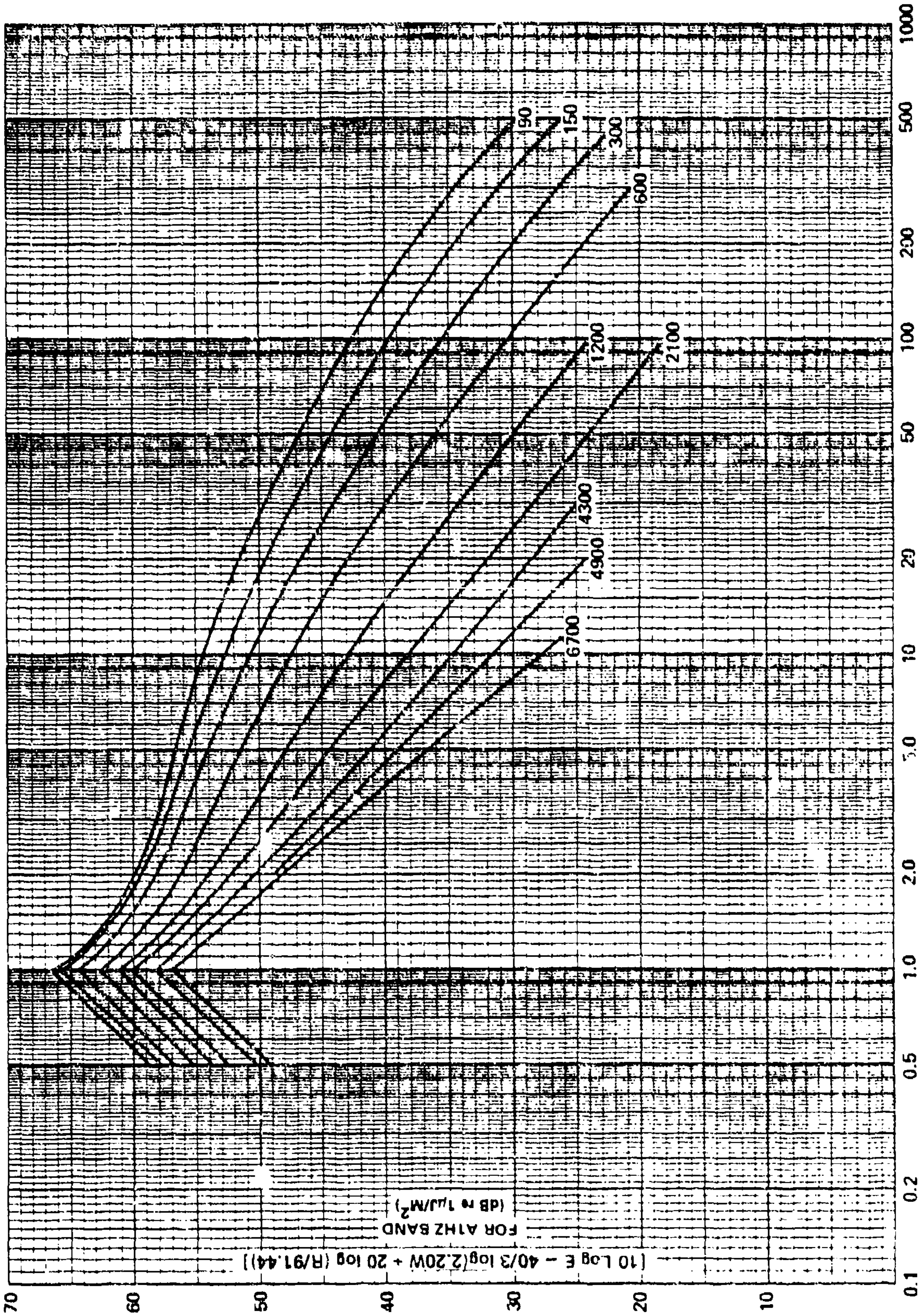


FIG. 18 SOURCE LEVELS FOR DEEP UNDERWATER EXPLOSIONS FOR VARIOUS BURST DEPTHS

TABLE 18 SOURCE LEVELS FOR DEEP UNDERWATER EXPLOSIONS
$[10 \log E - 40/3 \log (2.2W) + 20 \log(R/91.44)]$ (dB re : 1µJ/m^2/Hz)

	BURST DEPTHS (METERS)									
f/fb		6700	4900	4300	2100	1200	600	300	150	90
0.5		49.0	–	50.0	52.5	53.6	55.0	56.9	57.6	58.5
0.6		[illegible].2	–	52.3	54.4	55.7	57.0	58.8	59.8	60.5
0.7		52.7	–	54.0	56.0	57.2	58.8	60.2	61.5	62.3
0.8		54.4		55.6	57.5	58.7	60.2	61.9	63.0	64.0
0.9		55.8	–	57.0	58.9	60.0	61.6	63.2	64.5	65.2
1.0		57.0	–	58.0	60.0	61.1	62.6	64.2	65.8	66.2
1.5		52.0	–	53.5	55.0	56.5	58.3	60.0	61.2	61.8
2.0		48.0	49.0	50.3	52.3	54.0	56.2	58.2	59.5	60.0
3.0		43.0	44.7	46.0	48.7	51.1	54.0	56.2	57.6	58.0
4.0		39.2	41.5	43.3	46.2	49.2	52.8	55.0	56.4	57.3
5.0		36.3	39.0	41.2	44.6	47.9	51.7	54.0	55.5	56.8
6.0		34.0	37.0	39.7	42.8	46.7	50.6	53.2	54.9	56.0
7.0		32.1	35.5	38.0	41.4	45.6	49.7	52.7	54.3	55.7
8.0		30.6	34.0	36.8	40.2	44.5	48.8	51.8	53.8	55.2
9.0		29.0	32.8	35.7	39.0	43.8	48.0	51.2	53.3	54.8
10		27.9	31.8	34.8	38.1	43.0	47.5	50.8	52.8	54.4
15			27.3	31.0	34.7	39.8	44.9	48.4	50.9	52.9
20			24.2	28.6	32.0	37.4	42.9	6.7	49.5	51.6
30				25.0	28.6	34.0	40.0	44.0	47.2	49.5
40					26.0	31.8	37.8	42.0	45.8	48.0
50					24.0	30.0	36.0	40.8	44.4	46.9
60					22.8	28.5	34.7	39.5	43.1	45.9
70					21.3	27.0	33.5	38.3	42.0	45.0
80					20.0	25.9	32.3	37.5	41.2	44.0
90					19.0	24.9	31.5	36.5	40.6	43.2
100					18.0	23.8	30.6	35.8	39.7	42.6
150							27.0	32.5	36.8	40.0
200							24.5	30.0	34.[illegible]	37.8
300							21.0	27.5	31.0	34.5
400								24.0	28.4	32.0
500									25.2	29.8

CHAPTER 19. RATIO OF GRAM ATOMS OF ALUMINUM TO GRAM ATOMS OF OXYGEN (Al/O) FOR AN ALUMINIZED EXPLOSIVE MIXTURE

For mixtures containing aluminum (Al), the number of gram atoms is simply found by dividing the weight, in grams of the Al by its atomic weight, 27 (or multiply by 0.037).

The number of gram atoms of oxygen (O) in a given weight of high explosive (HE) is:

$$\frac{\text{(No. atoms of oxygen in empirical formula for HE)(Weight of HE, grams)}}{\text{(Molecular weight of HE)}}$$

For 100 grams of a mixture, the gram atoms of oxygen in a particular HE component is a constant times the HE weight percentage, when the composition is expressed in parts which total 100. The constants for calculating the oxygen content of some explosive materials are given below:

RDX	0.027	TNETB	0.0363
TNT	0.0264	BTNEU	0.0336
PETN	0.038	AP*	0.0341
AN*	0.0375		

(*AP is ammonium perchlorate, AN is ammonium nitrate)

For mixtures containing more than one HE material, the number of gram atoms of oxygen is the sum of those in each of the various HE components.

For a mixture of RDX/TNT/Al, the Al/O ratio would be:

$$\text{Al/O} = \frac{0.037 \text{ X } (\%\text{Al})}{0.027 \text{ X } (\%\text{RDX}) + 0.0264 \text{ X } (\%\text{TNT})}$$

For a mixture of PETN/TNT/Al, the ratio would be:

$$\text{Al/O} = \frac{0.037 \text{ X } (\%\text{Al})}{0.038 \text{ X } (\%\text{PETN}) + 0.0264 \text{ X } (\%\text{TNT})}$$

PROBLEM EXAMPLE:

Find the Al/O ratio for Torpex II (a 42/40/18) mixture of (RDX/TNT/Al).

PROBLEM SOLUTION:

$$(1)\quad Al/O = \frac{0.037 \times (\%Al)}{0.027 \times (\%RDX) + 0.0264 \times (\%TNT)}$$

$$Al/O = \frac{(.037)(18)}{(.027)(42) + (.0264)(40)}$$

$$AL/O = \frac{.666}{1.134 + 1.056} = \frac{.666}{2.190}$$

$$Al/O = 0.304$$

The information in this chapter is from:

"The Contribution of Al to the Effectiveness of an Explosion. I. Underwater Performance of One-Pound Charges," Christian, E. A., NAVORD Report 3760, Aug 1954.

CHAPTER 20. THE EFFECT OF ALUMINUM ON THE UNDERWATER POWER OF EXPLOSIVE MIXTURES

If the underwater performance of a non-aluminized explosive is known, the change in shock wave and bubble energies due to the addition of aluminum can be estimated from either the graph shown below or Table 20. The aluminized energy values relative to an equal weight of the non-aluminized material are plotted vs. the ratio of gram atoms of aluminum to gram atoms oxygen (Aℓ/O) in the mixture (See Chapter 20 for methods for calculating the Aℓ/O ratio for various high explosives).

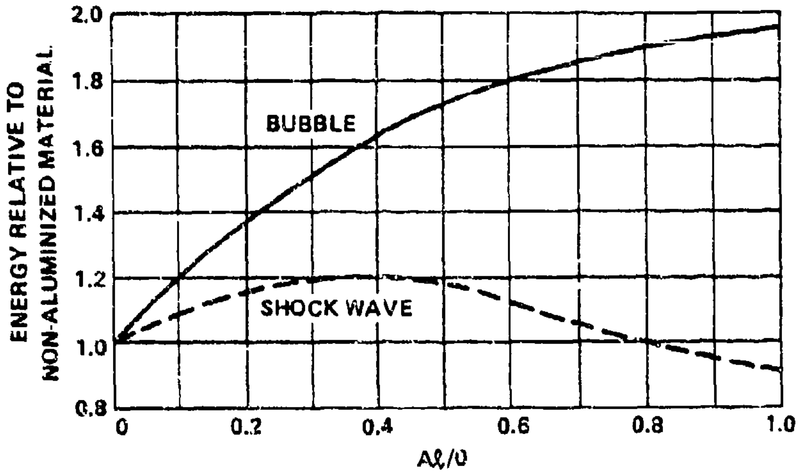


Figure 20. The Effect of Aluminum on the Underwater Power of Explosive Mixtures

The graph also applies to three-component systems such as mixtures of RDX/TNT/Al. In such a case, the value, for a particular aluminized mixture with a certain Al/O is relative to the non-aluminized mixture with the same high explosive matrix; i.e., the ratio RDX/TNT must be the same.

CAVEAT: The relationships discussed in this chapter were derived from diaphragm gage and bubble period measurements of 1/2-kilogram charges. The method will probably estimate within 10% the

performance of conventional explosive materials (those containing C, H, N, and O) but may not be applicable for radically different compositions.

PROBLEM EXAMPLE:

Estimate the shockwave and bubble energies of a mixture of 70% RDX and 30% aluminum.

SOLUTION:

(1) Calculate the Al/O ratio for this mixture:

$$Al/O = \frac{.037 \times (\%Al)}{.027 \times (\%RDX)}$$

$$Al/O = \frac{(.037)(30)}{(.027)(70)} = 0.59$$

(2) With this value of the Al/O ratio enter either the graph or table and obtain:

Shock wave energy = 1.12 times that of an equal weight of RDX

Bubble energy = 1.80 times that of an equal weight of RDX

(3) From Table 4-2 obtain $(W_{Dd})_{pent} = 1.10$ and $(RBE)_{pent} = 1.02$ for RDX

(4) Thus, the proposed 70/30 mixture would have:

$$(W_{Dd})_{pent} = 1.12 \times 1.10 = 1.23$$

$$(RBE)_{pent} = 1.80 \times 1.02 = 1.84$$

As a check on this method, Table 4-3 gives the measured values of $(W_{Dd})_{pent}$ and $(RBE)_{pent}$ as 1.26 and 1.86 respectively.

The information in this chapter is from:

"The Contribution of Al to the Effectiveness of an Explosion. I. Underwater Performance of One-Pound Charges," Christian, E. A., NAVORD Report 3760, August 1954.

TABLE 20 THE EFFECT OF ALUMINUM ON THE UNDERWATER POWER OF EXPLOSIVE MIXTURES

Al/O RATIO	SHOCK WAVE ENERGY RELATIVE TO NON-ALUMINIZED MATRIX	BUBBLE ENERGY RELATIVE TO NON-ALUMINIZED MATRIX
0	1.00	1.00
0.05	1.05	1.12
0.10	1.08	1.19
0.15	1.12	1.29
0.20	1.14	1.37
0.25	1.18	1.44
0.30	1.19	1.51
0.35	1.20	1.57
0.40	1.20	1.63
0.45	1.19	1.68
0.50	1.17	1.72
0.55	1.14	1.76
0.60	1.12	1.80
0.65	1.09	1.83
0.70	1.04	1.86
0.75	1.02	1.88
0.80	1.00	1.90
0.85	0.97	1.91
0.90	0.94	1.92
0.95	0.92	1.94
1.00	0.91	1.96

CHAPTER 21. THE EFFECT OF CHARGE DENSITY ON THE UNDERWATER EXPLOSIVE PERFORMANCE OF TWO EXPLOSIVES: HBX-1 and 55/40/5 TNT/Al/Wax

The underwater output (explosive performance) of explosives can be a function of the density of the explosive. The table and figures presented below were determined for small (0.5 kg), pressed, cylindrical charges with a conical booster. Similar trends were noted for cast charges. Pentolite was found NOT to exhibit any output variation with density.

(Note: %TMD is defined as the percentage of the theoretical maximum density for a particular explosive).

PROBLEM EXAMPLE:

Compare the shock wave and bubble energies of HBX-1 at 85% TMD and at 98% TMD.

SOLUTION:

(1) From Table 21:

$(W_{Dd})_{pent}$ = 1.15 at 85% TMD

$(W_{Dd})_{pent}$ = 1.01 at 98% TMD

$(RBE)_{pent}$ = 1.49 at 85% TMD

$(RBE)_{pent}$ = 1.40 at 98% TMD

This means that at 85% TMD, the shock wave energy of HBX-1 is 1.15 relative to a pentolite standard while at 98% TMD the shock wave energy of HBX-1 is down to 1.01 relative to that same pentolite standard. The same trend, but not of the same magnitude can be seen for the relative bubble energy. At 85% TMD, the RBE of HBX-1 is 1.49 relative to a pentolite standard, while at 98% TMD, the RBE is down to 1.40 relative to that same pentolite standard.

The information in this chapter is from:

"Comparison of the Underwater Power of Explosives in Small Charges -- XI Further Development of Test Procedures," Heathcote, T. B., and Niffenegger, C. R., NOLTR 67-17, 3 March 1967.

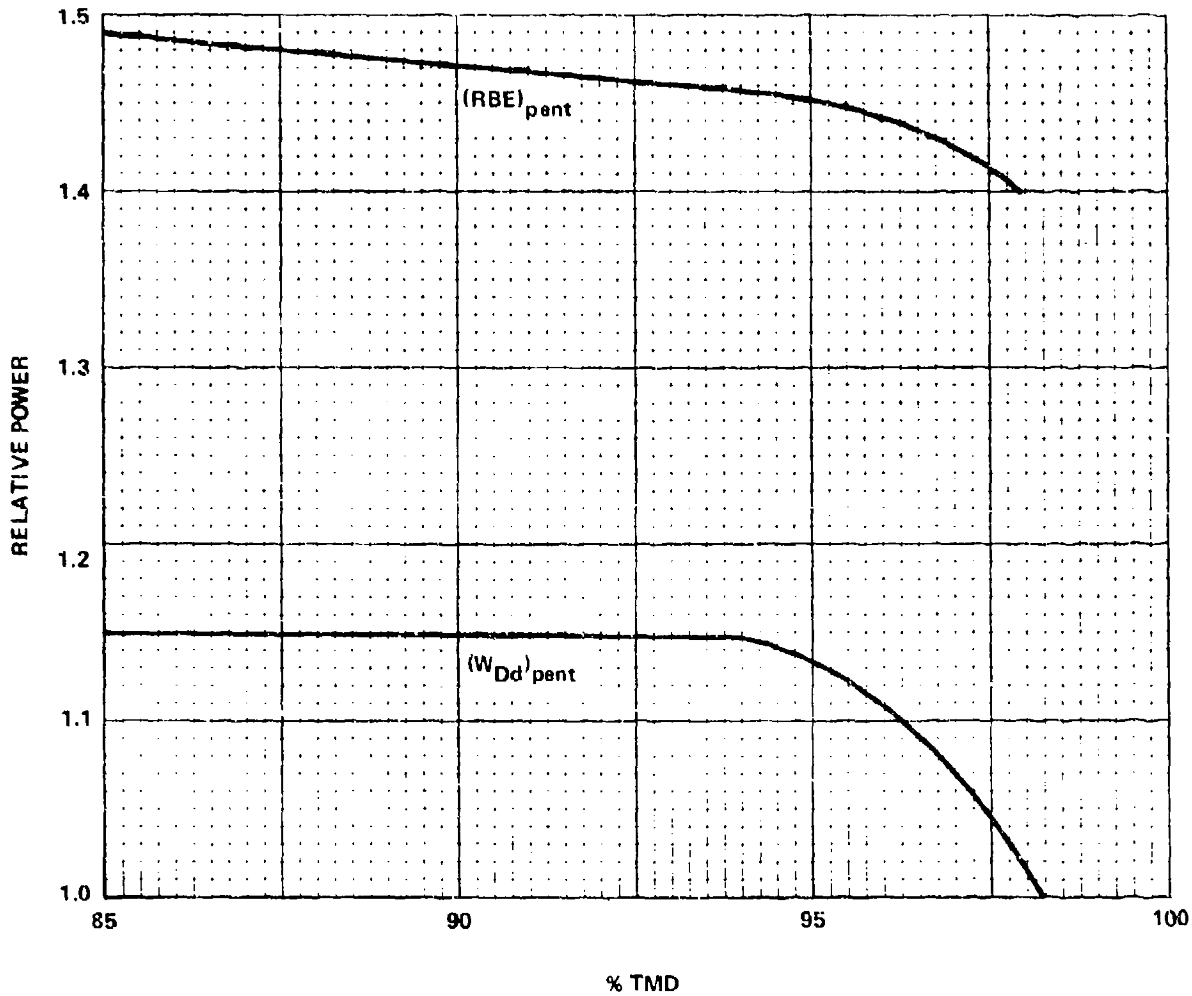


FIG. 21-1 THE EFFECT OF CHARGE DENSITY ON THE UNDERWATER POWER OF SMALL CYLINDERS OF HBX-1

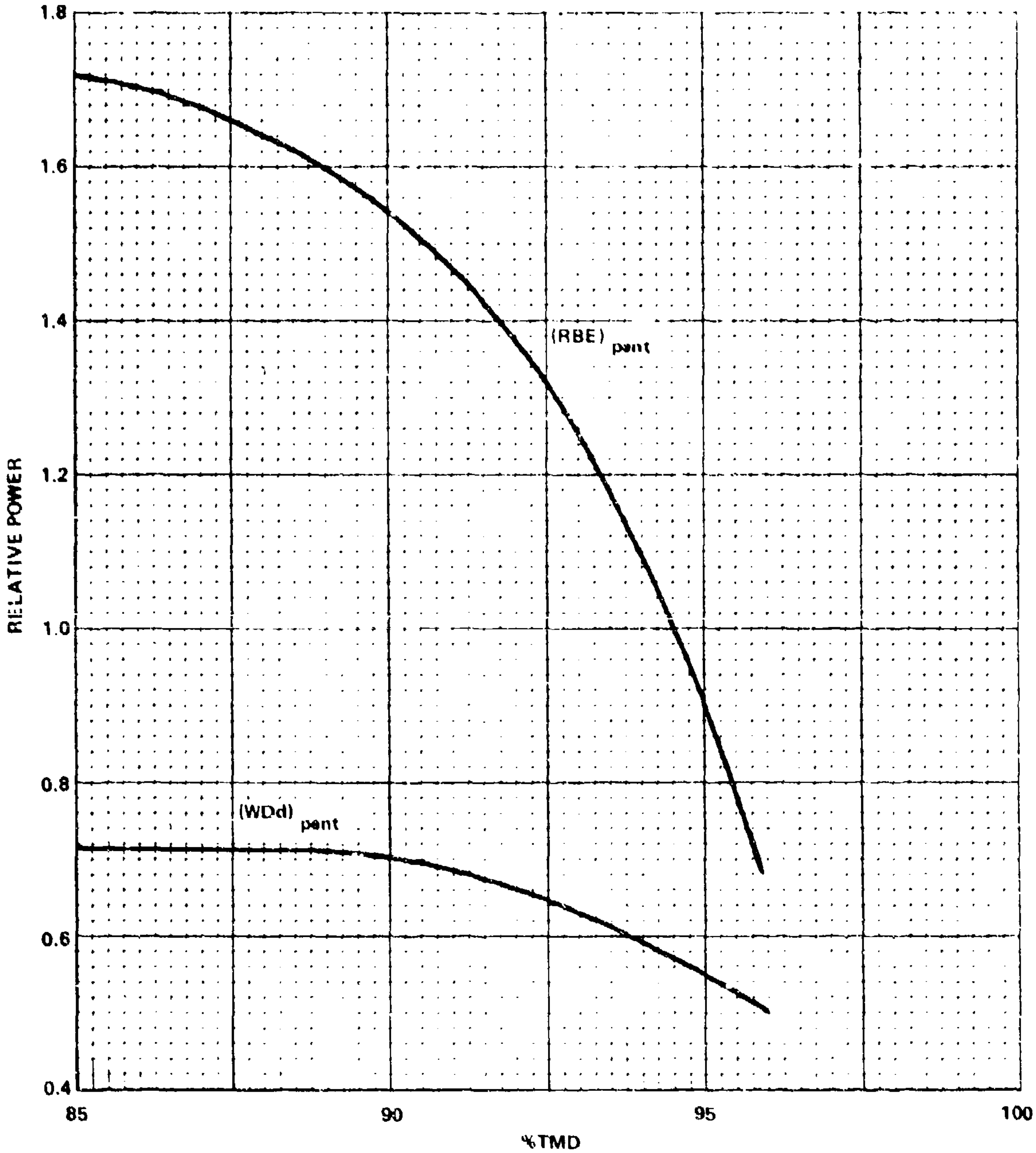


FIG. 21-2 THE EFFECT OF CHARGE DENSITY ON THE UNDERWATER POWER OF SMALL CYLINDERS OF 55/40/5 TNT/Al/MAX

TABLE 21 THE EFFECT OF CHARGE DENSITY ON THE UNDERWATER PERFORMANCE OF TWO EXPLOSIVES

	HBX-1		55/40/5 TNT/Al/WAX	
%TMD	$(W_{Dd})_{pent}$	$(RBE)_{pent}$	$(W_{Dd})_{pent}$	$(RBE)_{pent}$
85	1.15	1.49	0.71	1.72
86	1.15	1.49	0.71	1.70
87	1.15	1.48	0.71	1.68
88	1.15	1.48	0.71	1.64
89	1.15	1.48	0.71	1.60
90	1.15	1.47	0.70	1.55
91	1.15	1.47	0.68	1.47
92	1.15	1.47	0.66	1.39
93	1.15	1.46	0.63	1.27
94	1.15	1.46	0.60	1.11
95	1.13	1.45	0.55	0.90
96	1.11	1.44	0.50	0.67
97	1.07	1.43	–	–
98	1.01	1.40	–	–

CHAPTER 22. A METHOD OF ESTIMATING THE UNDERWATER PERFORMANCE OF AN EXPLOSIVE MIXTURE

The underwater shock wave and bubble energy of a mixture of "conventional" explosives, i.e., those that contain C, O, N, and H in the molecule, can be estimated if the shock wave and bubble energy of each component of the mixture is known. The energy contribution of each component is given by the product: energy of the component times the weight fraction of the component present, i.e.,

$$E_{mixture} = \Sigma x_i E_i \qquad (1)$$

where x_i is the weight fraction of component i and E_i is the $(W_{Dd})_{pent}$ or $(RBE)_{pent}$ of component i.

PROBLEM EXAMPLE:

Estimate the ratio of the energy relative to pentolite for a 40/40/20 mixture of RDX/TNT/PETN.

SOLUTION:

(1) From Table 4-2 obtain the values of $(W_{Dd})_{pent}$ for each of the constituents, i.e.,

RDX	1.10
TNT	0.84
PETN	1.15

(2) Substitute these values of E_i along with their corresponding x_i's into Equation 1

$$E_{mixture} = (.40)(1.10) + (.40)(0.84) + (.20)(1.15)$$

$$E_{mixture} \quad \text{(relative to pentolite)} = 1.01$$

The information in this chapter is from:

"Dependence of Damage Effects Upon Detonation Parameters of Organic High Explosives," Price, D., NAVORD Report 6703, August 1959.

CHAPTER 23. RELATION BETWEEN INVERSE SCALED DISTANCE, NUMBER OF CHARGE RADII, AND CHARGE DENSITY

There exists a relationship between the density of an explosive charge and the number of charge radii corresponding to a particular scaled distance:

$$\bar{R}\,V = (4\pi\rho/3)^{1/3} \tag{1}$$

$$\bar{R}\,V = 1.612\rho^{1/3} \tag{2}$$

where:

$\bar{R}$ = slant range in charge radii = R/a

R = slant range (m)

a = ch ge radius (m)

V = inverse scaled distance = $W^{1/3}/R$ ($kg^{1/3}/m$)

W = charge weight (kg)

ρ = charge density (kg/m^3)

Equation (2) is plotted in Figure 23 and tabulated for a wide range of charge densities in Table 23.

PROBLEM EXAMPLE:

An inverse scaled distance of 1.5 $kg^{1/3}/m$ corresponds to how many charge radii from a pentolite charge?

SOLUTION:

(1) From Table 1, ρ for pentolite is 1710 kg/m^3

(2) From either Equation (2), Figure 23, or Table 23 (with suitable interpolation), read:

$\bar{R}\,V = 19.28\ kg^{1/3}/m$

(3) $\bar{R} = 19.28/V = 19.28/1.5$
$\bar{R} = 12.85$ charge radii

TABLE 23 RELATION BETWEEN INVERSE SCALED DISTANCE, NUMBER OF CHARGE RADII, AND CHARGE DENSITY

CHARGE DENSITY (kg/m^3)	$\bar{R}V$ ($kg^{1/3}/m$)
1200	17.13
1250	17.36
1300	17.59
1350	17.82
1400	18.03
1450	18.25
1500	18.45
1550	18.66
1600	18.86
1650	19.05
1700	19.24
1750	19.43
1800	19.61
1850	19.79
1900	19.97
1950	20.14
2000	20.31
2050	20.48
2100	20.64
2150	20.81
2200	20.97

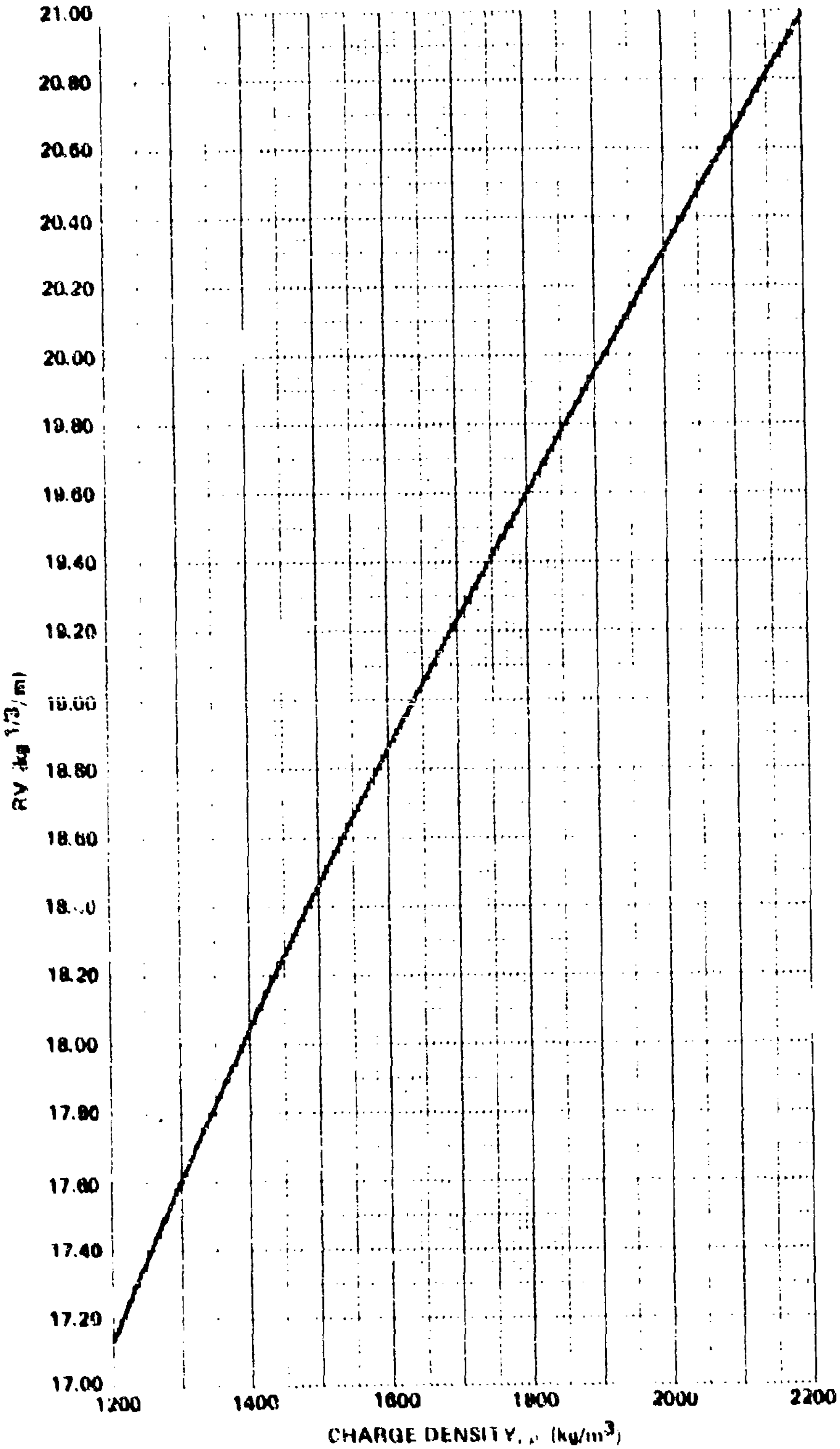


FIG. 23 RELATION BETWEEN INVERSE SCALED DISTANCE, NUMBER OF CHARGE RADII, AND CHARGE DENSITY